Doctor of Philosophy

ARCH1229B PhD (Ind Des) by Project

The Production of Power by Pure Rotary Means

A record of a lifetime of study of the parametric, mechanical design of a rotary engine

Durable Visual Record

27th March 2008

RMIT University

SCHOOL of ARCHITECTURE and DESIGN

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Prologue

PhD (Industrial Design) by Project

The Production of Power by Pure Rotary Means: A Study in Designing and Making

This PhD is a demonstration of the application of many years of diverse designing experience to the design of a new pure rotary engine. The first two chapters offer a collection of observations on Design and Industrial Design, garnered over a lifetime of designing and design management. It is worth summarising my background at this point to indicate the range that is drawn upon in the PhD. My experience includes an Aircraft Precision Sheet Metal apprenticeship at Commonwealth Aircraft Corporation during the period of the Sabre jet fighter and the Wingeel trainer projects. During this seven year period I endeavoured to complete a Mechanical Engineering diploma, at night school, at the Melbourne Technical College. I was not able to complete this labour.

However the result was enough to get myself hired as an “Appliance Designer” at Radio Corporation designing “white goods” such as washing machines, air conditioners, refrigerators and dishwashers. These were marketed under the Astor and Servex brands.

The next phase was as Senior Industrial Designer at Rosenfeldt Gherardin and Associates, a firm of Industrial Designers and Architects. They were the foremost Industrial Design practice at that time. It was an action packed, exciting seven year period designing “consumer goods” for a myriad of clients.

The next interlude was at Varian Techtron where I was responsible for the mechanical Research and Development of a series of atomic absorption and ultraviolet-visible spectrophotometers. Another seven year period, during which I won the scientific section of the Prince Phillip Prize for Industrial Design in 1968 for the design of the AA7 atomic absorption spectrophotometer an analytical instrument capable of determining the content of lead in urine and calcium and potassium in blood to decimals of a part per million.

I then moved to General Electric (Appliances) Australia as resident Industrial Designer designing “shelf items” such as kettles, irons, mixers, vacuum cleaners and toaster ovens.

Yet another seven year period during which I won the Prince Phillip Prize for Industrial Design outright in 1978 for the design of the KE12 plastic electric kettle.

In 1980, I formed my own Industrial Design practice: Barry Hudson Industrial Design Pty Ltd. A large variety of products have been designed for a diverse collection of clients. These ranged from a series of high power lasers to pool and spa equipment The practice is still active although scaled down currently because I became blind with cataracts in 1987 and regained most of my eyesight again after inter-ocular implants in both eyes in 1988.

As a consequence of this I decided to investigate the possibility of teaching. I was welcomed at Monash University in 1989 as a sessional lecturer in Industrial Design. In 1992 I became a sessional lecturer in Industrial Design at RMIT University, advising and assisting the Honours students. In 1993 I joined RMIT as a full time tenured Industrial Design lecturer. I lectured at RMIT for ten years, during which, I completed a Masters Degree in Industrial Design (by project). The project was titled “A Laser Machining Centre”. The machine was designed to produce extremely accurate parts from CAD models from a very wide selection of materials. Including ceramics like Partially Stabilised Zirconia, woods, plastics, all stable metals and even gemstones. Sub-micron surface finish would be possible. It would be possible to remove material, add material by powder fusion and surface heat-treat all in the same setup.

The PhD has drawn the threads of this experience together and woven them through a lifelong obsession with rotary power. The chapters subsequent to the design discussion describe the evolution of the project. During the progression of the project, four case studies were undertaken. Each of these case studies involved the design of an engine, using the principles expounded in the early chapters. The parts of three of these were manufactured. The project has culminated in case study four which consisted of the conception, design and component manufacture of a new type of engine: the Hudson 5 Cycle Rotary Engine. It does not reciprocate, nor is it orbital (Sarich) and is not peritrocoidal (Mazda). It operates with pure rotary motion. It also promises to have a favourable environmental aspect due to its excellent fuel efficiency and because of its exceptional power to weight and power to size ratios plus a low component count. The small size and low number of parts make it very economical to produce, both in materials and energy.

Acknowledgements

I wish to express my deep appreciation to Leonie who has manifested extreme patience and forbearance during this exercise, and for her help to bring this project to the stage at which it finds itself.

RMIT University

Prof. Peter Downton. Senior supervisor. Who is a ‘petrol-head’ himself, as well as being a dedicated academic. He has contributed to this project immensely. His enthusiasm, encouragement and engagement, as well as his fully appreciated advice, is reflected in what is presented here.

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Athol Chapman. Who has made the whole thing a little easier than it might have been.

Paul Pile. 3D modelling is serious stuff indeed.

John Mepsted. Whose contacts are manifest.

External

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Mark Hardman. Of Hardman Bros. The Gears and shafts are beautiful.

QMI. Queensland Manufacturing Institute. Who produced investment castings of the rotors and endplates of exceptional quality from the 3D CAD drawings.

Graham Hume. Of Hume Bros. My cobber and confidant during this process. His expertise, enthusiasm and physical help have greatly engendered its completion.

1

Introduction: The Production of Power by Pure Rotary Means

Aesthetics

Pure rotary motion carries with it an intrinsic beauty. The advantages of virtually vibrationless power are fundamental to our basic aesthetic appreciation. Reduced audible mechanical noise would also be a valuable asset. Electric motors and turbines have this attribute. Reciprocating engines do not.

Vibration

All through the history of reciprocating engines, an immense effort has been expended in an endeavour to reduce the effect of vibration. The careful design of the counterweighing of a crankshaft is vital. Matching the static weights of the pistons, gudgeon pins and conrods is important. Dynamic balancing of the crankshaft assembly is crucial to this exercise since its action is essentially eccentric. Potentially damaging critical frequency vibration zones, amid the revolution range, are usually changed by adding an harmonic balancer, of a selected mass, to the front of the crankshaft. Mitsubishi has an additional chain driven balance shaft to help negate the deleterious sensation of vibration. It is very effective, and justifiably, absorbs an additional amount of power, but it is after the act. It would be much better if a device of this type was not necessary.

The vibration resulting from variation in the torque output is normally dampened by the flywheel. The more pistons an engine has, the smoother the torque output should be.

If an engine could be produced which moved in a pure rotary fashion, it would reduce the vibration level drastically.

Noise

In addition to the low frequency vibration there is a substantial amount of higher frequency audible noise generated by the valve drive train. The timing chain, camshaft/s, cam-followers, rockers, tappets, valves and valve springs all contribute to the noise level emitted by a reciprocating engine.

Energy

Reciprocating engines have an eccentric crankshaft with a conrod, gudgeon pin, and piston assembly. All of which moves through a nearly sinusoidal acceleration – deceleration cycle, from momentarily stationary at the top, to maximum speed in the middle, to stationary at the bottom, to maximum speed again at the middle, to stationary again at the top. The amount of conrod flex is a major consideration when designing a reciprocating engine. This is an indication of how much energy is expended, and is all needlessly consumed energy. A pure rotary motion engine could regain all the energy lost to the reciprocation action, with a corresponding gain in efficiency.

Environment

If an engine, of a given power output, could be designed to be smaller, lighter and simpler, the result would be reduced material usage and a reduction in the energy used to produce it. Improved thermal efficiency is also an important part of the design aim and would reduce fuel usage. An almost silent engine with reduced vibration would also help to reduce noise pollution.

2

On Rotary Machines

Rotary Pumps and Engines

Rotary machines have been around for a very long time. There is a plethora of examples in the patent records of each country. They are all interesting, but unfortunately, many of them are not viable.

The following page shows twelve diagrammatic examples of **single shaft, vane-type rotary machines.** They are all pumps but may be used as motors if an external source of pressure is introduced. They are my own interpretation of illustrations to be found in 'Rotary Piston Machines' by F. Wankel, which is a very thorough attempt to classify rotary machines, and 'Rotary Engine' by Kenichi Yamamoto, which is a description of the engineering history of the NSU-Wankel rotary engine.

N**o. 1** The earliest is the Ramelli water-pump dated 1588.

No. 2 depicts the Watt rotary steam engine.

No. 3 introduces an internal vane stabilization ring.

No. 4 incorporates a scotch yoke.

No. 5 shows an improvement on No.3.

Nos. 6 and 7 are orbital and consequently require the rotor to be stabilized directionally, while being rotated eccentrically by the crank.

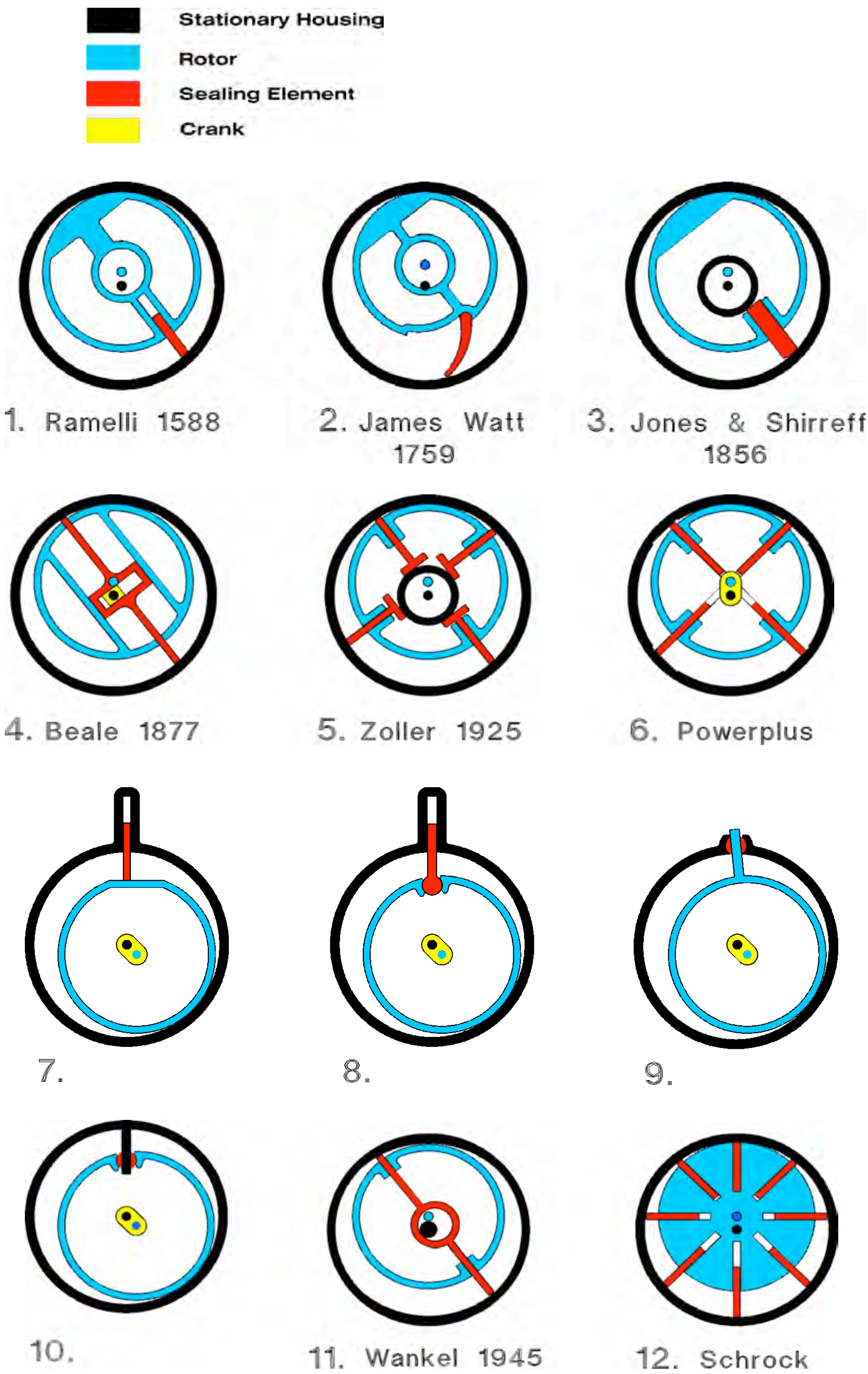
Nos. 7, 8 and 9 are variations on the cranked rotor theme.

No. 10 is my own addition to the collection. It seemed to me to be the logical extrapolation of Nos. 7, 8 and 9.

No. 11 is an early design by Felix Wankel.

No. 12 has been a popular choice for supercharging many an MG TC during the 1950s and early '60s.

Single-Shaft Vane Type



Two Shaft - Interacting Rotor Type

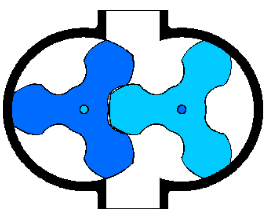
There are also a great many examples of two shaft machines. They are generally dependent on precision fit to maintain sealing. The four following diagrammatic examples are typical of the genre.

No. 1 The Roots blower has been used in many applications, including the cabin pressurization of propeller driven aircraft. Jet driven aircraft tend to pressurize the cabin from one of the compression stages of the engine. Many diesel engines have been supercharged by Roots type blowers, especially large diesel engines, both two-stroke and four-stroke installations, like trucks, ships and power generation plants.

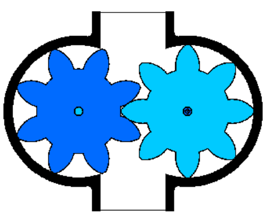
No. 2 is a representation of the Gear Pump. This has been used extensively in industry as a fluid pump. A notable example is its use as an oil pump in a large number of reciprocating engines.

No. 3 is a simplified expression of a 2:1 ratio version of the profiles devised by myself for use as an axial flow screw compressor and motor applied to engine no 2, mentioned in Prior Hudson Engines on page 39. It was intended to be helical with one and a half turns. The profiles currently in common use as air compressors are ground asymmetric with radii along the tooth tips. This results in a substantial leakage, or ‘slippage’ path. They are oil flooded and self-driven, without timing gears. The oil must be subsequently extracted and the ‘slippage’ is compensated for by running at a higher speed. My profiles are difficult to grind by conventional means. The solution to this problem is to use a helical broach for the finishing operation. Timing gears would render the system oil-less and obviate the need for the oil extraction process.

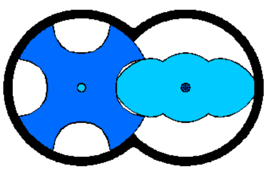
No. 4 depicts a four toothed version of the 1:1 ratio devised by myself in 1993 as mentioned on page 39. This concept eventually culminated in engine No. 6 as a six toothed, straight-cut version with sealing means added.



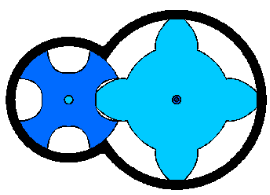
1. Roots



2. Gear Pump



2:1
3. Hudson 1970



1:1
4. Hudson 1993

On Rotary Engines

Niclolaus August Otto succeeded in making the first internal combustion engine work effectively in Germany in 1876. Ten years later, 1886, Gottlieb Daimler utilized an engine of this type in the first automobile. These were both reciprocating Engines.

The first rotary machine was the Ramelli water pump in Italy in 1588. Sealing has always been the problem with rotary machines, which is probably why Otto decided on the reciprocating principal. Cylindrical pistons are much easier to seal.

NSU-Wankel engine

The most successful rotary engine design has been the NSU-Wankel. The most informative source on this subject is 'Rotary Engines' by Kenichi Yamomoto.

The engine started life when NSU co-opted Dr. Felix Wankel to design a supercharger for application to a motorcycle engine. This resulted in the peritrochoid compressor in 1951. The NSU bike attained a world speed record in the USA that year.

The collusion between NSU and Wankel resulted in the NSU-Wankel engine. NSU developed the engine to a stage where it attained 100 hours running time in 1959.

The first installation in a car was, by Toyo Kogyo (Mazda), in the prototype Cosmo Sports in 1963. The NSU Spider was introduced onto the market in 1964 using a 500cc, single rotor version of the engine. In1967, NSU released the Ro 80 and Toyo Kogyo the Cosmos. Both were fitted with 1000cc two-rotor versions. (In 1969 NSU became Audi by merger.)

At that time the Victorian marketing manager for Mazda was my next-door neighbor and he brought home a market sample of the Cosmos. I was invited to 'take it around the block'. I discovered that it was capable of revving its 'ring' off. I returned the car twenty minutes later (in one piece) with my ears severely plastered back. I gave it a glowing report, but it was not sold in Australia. A great pity.

. Licensers and Licensees of the NSU-Wankel Engine (as of 1977)

Licensers

Country	Company	Field of Application
WestGermany	ComotoAudi NSU Auto Union AG Wankel GmbH	Motor vehicles

Licencees

Country	Company	Field of Application
West Germany	Fichtel & Sachs AG Klockner-Hamboldt-Deutz AG Daimler-Benz AG MAN (Maschinenfabrik Augsburg Nurnberg AG) Friedrrich Krupp GmbH Dr. Ing. H.c.F. Porsche AG Johannes Graupner	Boats, Land vehicles and Industrial purposes All technical fields All technical fields All technical fields All technical fields Motor vehicles Model Engines
Luxemburg	Comotor S.A. (Peugeot/Citroen)	Motor vehicles
Great Britain	Rolls-Royce Motors Limited NVT Motorcycles Ltd.	ll technical fields Motorcycles
Switzerland	CROCO Engines GmbH Off-road vehicles	
United States	Cumtiss-Wright Corporation Outboard Marine Corporation Ingersoll-Rand Company American Motors Corporation General Motors Corporation	All technical fields Boats and Industrial purposes Industrial purposes Motor vehicles All fields excepting airplanes
Japan	Yanmar Diesel Co., Ltd. Toyo Kogyo Co., Ltd. Nissan Motor Co., Ltd. Toyota Motor Co., Ltd.	All technical fields excepting motor vehicles All technical fields Passenger cars Passenger cars

The table above is quoted from ‘Rotary Engines’ by Kenichi Yamomoto on the utilization of the NSU Wankel engine, the companies involved and their location.

Mazda have sold the engine in Australia in the RE series with the 12A two-rotor engine. A larger version, the 13B was installed in the RX7 and the latest is a three-rotor version installed in the RX8.

The NSU Wankel has been used in many applications by a number companies. I list the table above because there is a parallel in the probable applications of this Five Cycle Engine to those of the NSU Wankel for the same reasons.

I am a member of ‘Team Grandpa’ and we have campaigned a series of racing cars in the Sports Sedan Class for the past eighteen years with some success. Almost all the cars were fitted with ‘full-house’ 13B engines (Mazda RX7) delivering about 320 hp at 9500 RPM

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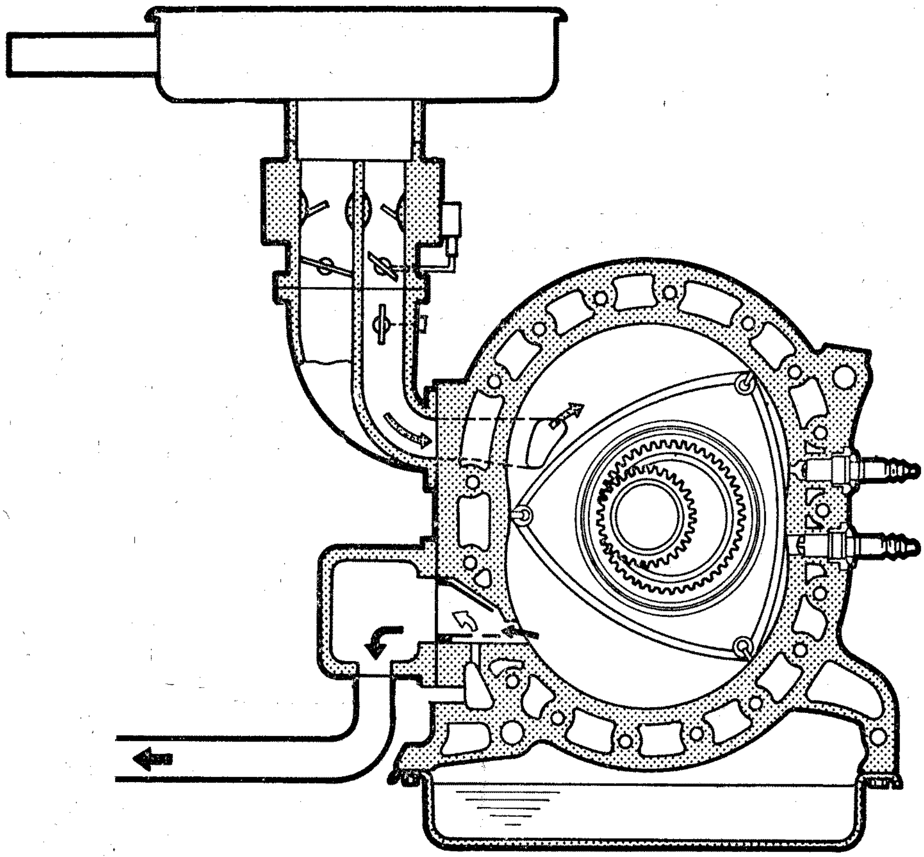


Cross-section through the NSU-Wankel Engine

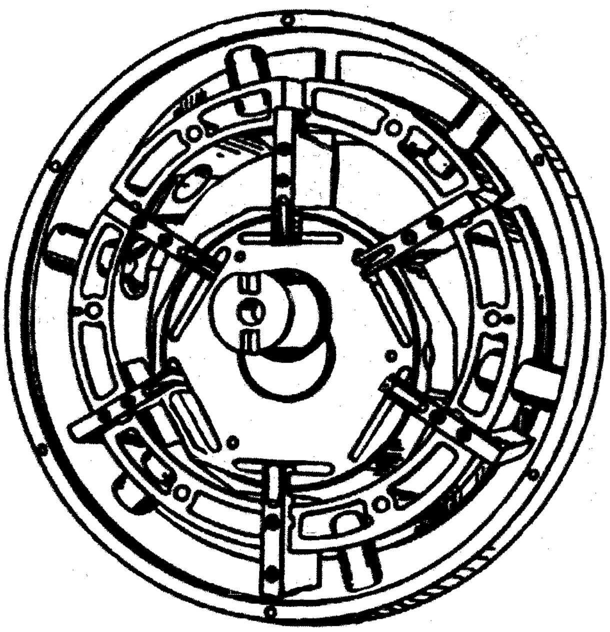
The diagram above is an edited version of an illustration on page 56 of ‘Rotary Engines’ by Kenichi Yamamoto published in 1981 by Sankaido Co., Ltd.

Australian Designed Engines

Sarich Orbital Engine

The Sarich Orbital engine was introduced to the public by the ABC on 'The Inventors' program. In 1973 a joint venture was formed with BHP (Broken Hill Proprietary Company Limited) to develop and commercialise the engine. 1978 saw the prelude of an improved direct injection system, which introduced air with the fuel. This system helps the atomization and vaporization process. Development of the orbital engine was abandoned. Attention was turned to the development of a two-stroke engine employing the new direct injection system.

The Orbital Engine Company currently enjoys worldwide success with its direct fuel injection system, the two-stroke engine, and offers an intellectual property consultancy and engineering services.



The Sarich Orbital Engine

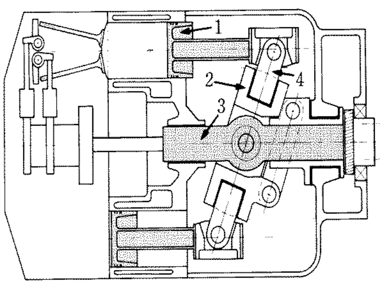
The diagram is an edited version taken from the Commonwealth of Australian Patent Specification No 467,415 granted to Tony Ralph Sarich on 11th January 1973.

Skalzo CVS Engine

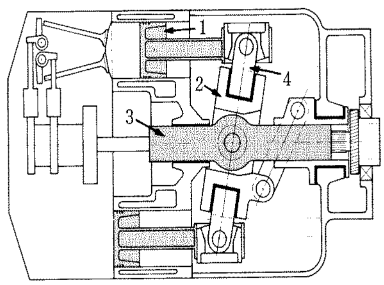
Joseph Skalzo devised the continuously-variable-stroke crankless engine. It is a five cylinder engine based on a variable angle wobble plate (or swash plate). It allows the engine capacity to be varied according to power demand. The aim was to reduce fuel consumption and exhaust emissions during the normal varied ‘usage profile’ of an automobile engine.

A long conversation with Joe Skalzo in 1983 prompted me to contrive engines Nos 3. and 4., mentioned in Prior Hudson Engines on page 41.

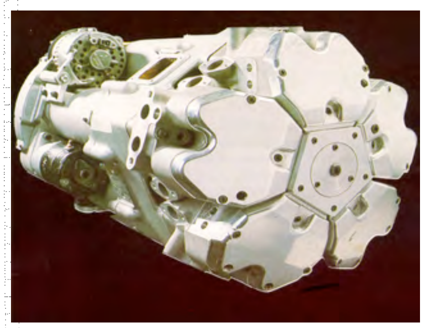
The engine was developed by Skalzo Automotive Research Limited and received worldwide recognition. An immense amount of effort was expended on the project. It was installed in a VR Commodore and was exhibited in the USA to some acclaim. Development of the engine was abandoned in 1998 when it was found that performance above 4000 RPM was deleterious due to excessive inertia. Another pity.



Maximum Stroke



Minimum Stroke



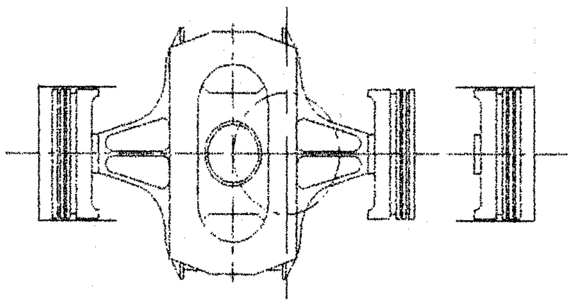
Skalzo CVS Engine

Joe is currently working on a system to disconnect various numbers of pistons, in reciprocating engines, from the crankshaft and reconnect them as the power demand dictates. He has the same aim using a different method.

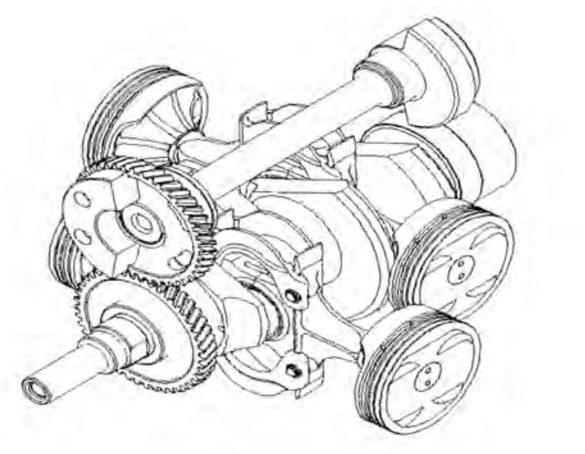
The SYTech Engine

The SYTech engine was developed initially at Melbourne University and susequently by CMC Power Systems in Sydney. The 414 version has been installed in the aXcessaustralia LEV (Low Emissions Vehicle) hybrid car and the 422 version in a Subaru Liberty. Worldwide interest in the engine has been expressed.

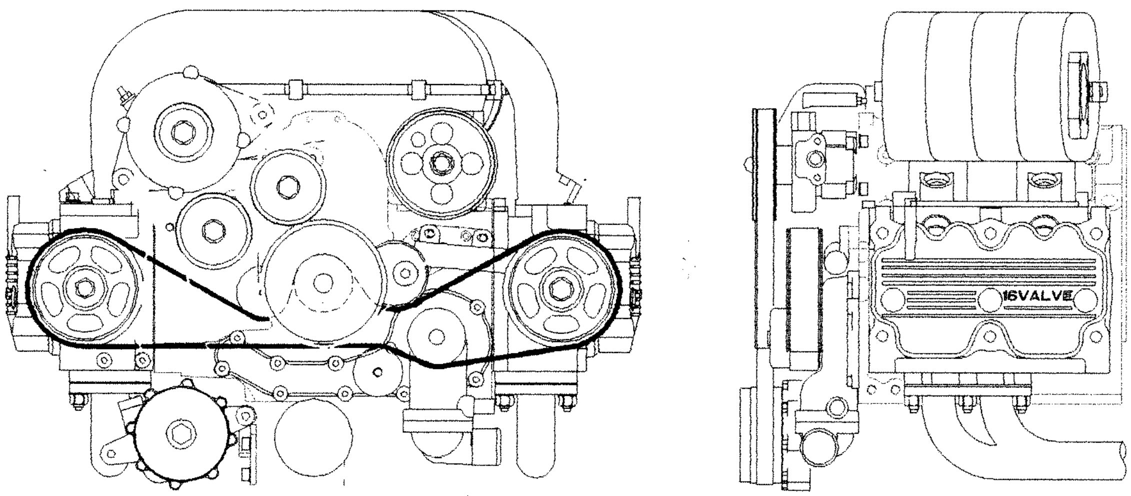
The engine is based on the scotch yoke mechanism. The scotch yoke replaces the gudgeon pin, connecting rods and big end bearings with ‘C yoke’ connected directly to two horizontally opposed pistons. A ‘linear slider bearing’ block runs vertically in the ‘C yoke’ and radially on a normal style crankshaft.



Scotch Yoke Mechanism



SYTech Internals



The 2.2 Litre 4 Cylinder SYTech Engine CMC 422

The diagrams are edited versions of those in an article by Dr.-Ing. Hans G. Rosenkrank

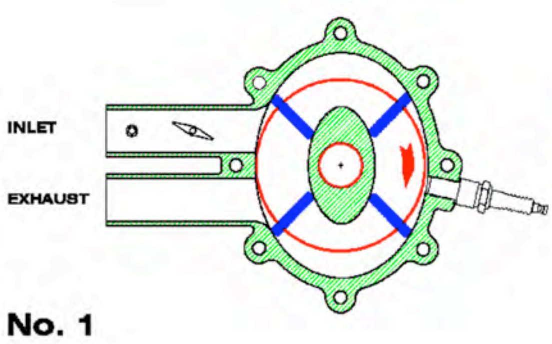
3

Prior Hudson Engines

The Quest

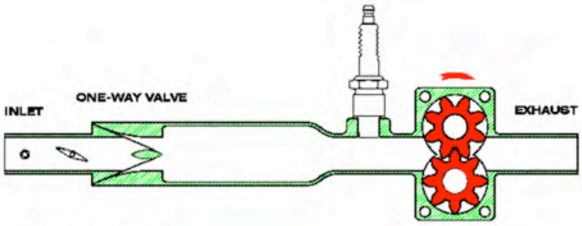
I was eight years old and it was summer. A rusty weed-grown hulk of a car lurked in the shadows of the pine tree behind the hay shed, inviting my cousin and I to discover its mysteries. It was a model "T" Ford. It took us the remainder of the Christmas holidays, and every farm tool on the place, to expose its inner workings.   The nest of machinery, which had been housing a community of wildlife, hid amazing secrets. We uncovered the mysteries of a reciprocating engine, a two-speed epi-cyclic gearbox and a two-speed differential. This early voyage of discovery ignited the curiosity that drove the rest of my life.

Six years later I found myself doing dishes with my sister to delay my homework. As my mind idly wandered, I realised with a thrill of anticipation that an engine need not necessarily take the form of that first engine. I dreamt of creating an engine, which would give power from pure rotary motion. Later I discovered that someone else had got there first, and invented the jet turbine. My enthusiasm was unabated and the **'rotary dream'** has persisted.

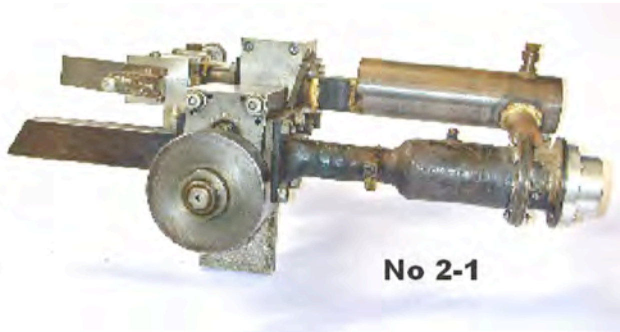


My first engine (No.1) manifested itself on the train coming home from night school at "Melbourne Tech" when I was eighteen. It was an internal combustion four-stroke, Otto cycle, vane type engine. The significant advantage was that each of the four chambers fired every revolution. It took some years to design and build a 125 cc working model. In 1964, I was senior designer for a firm of Architects and Industrial Designers and it was part of my brief to review the latest international patents. I found a diagram of an identical engine in *manufacturing* journal. The engine was popping and banging and looking very promising, but I was that crucial bit too late. This dimmed the '**dream'** for a time, but it persisted.

The basis of my second engine (No.2) occurred to me while I was building an aluminium body on a racing car late one wet night in 1969. It was a positive displacement pulsejet. The first trial model was made from a "Peugeot" oil pump. It took one day to build, and it worked. The second model was based on a pair of 'Holden' oil pump gears and ran to 10,000 revolutions per minute. This engine has subsequently been modified to include a compression stage (No 2-1).



No. 2

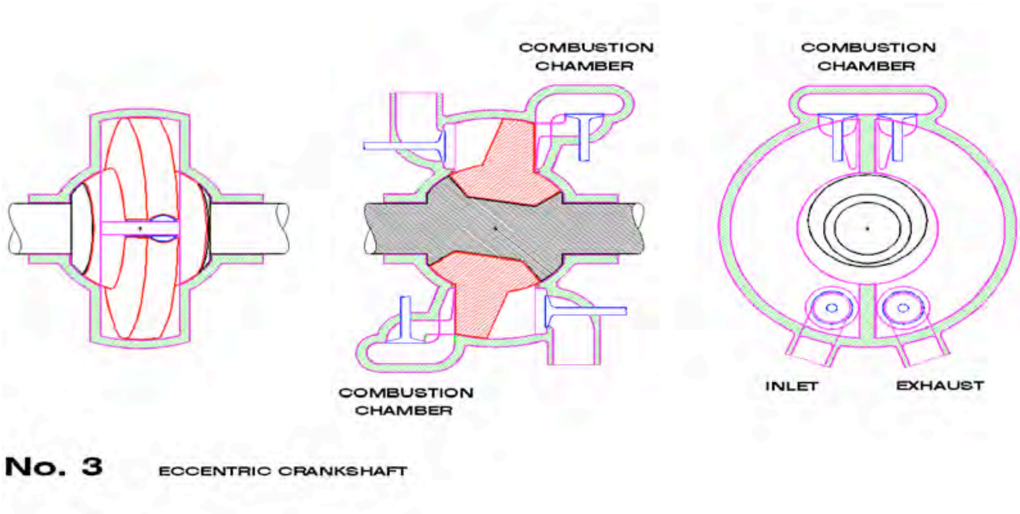


No 2-1

Both versions of engine No.2 were based on straight-cut spur gears, which could not be expected to produce the compression ratio needed, let alone contain combustion pressure. Early in 1970, in an attempt to increase the compression pressure, I reasoned that if the gears were to take a helical form, and were long enough to allow several teeth to be engaged simultaneously, it would be possible to have multiple simultaneous seal lines. This may have allowed compression pressures of well above 100 pounds per square inch in one stage. This realization precipitated an intensive investigation of possible profiles and ratios, which would enable this new type of compressor. The normal involute gear profile was not suitable.
The first successful profile was at a ratio of 2:1 with equal sized rotors. Many other ratios were also feasible, but I was not able to discover the profile to suit the ratio of 1:1. The 1:1 ratio has a basic aesthetic appeal.

In 1973, this machine was introduced onto the market as the axial-flow rotary screw compressor. The profile was different to mine, but the overall principal was the same. There are quite a few firms manufacturing rotary screw compressors these days. The leading brand is Atlas-Copco 'Silentair'.

In 1993, I had an interesting discussion with Anthony Kitchener of Cash Engineering, who is involved in research on screw compressors. This inspired me to re-visit the elusive 1:1 version. I eventually found the controlling factor: the outside diameter of the female profile must be the equal to, or less than, the root diameter of the male profile. This was an extremely interesting, but practically useless, piece of information (at that time).



Engines No. 3 and No. 4 were based around the swash-plate. Like the previous engines, I found them fascinating, but both these approaches, although ideal for low-pressure pumps, became complex when applied as an engine.

Many other ideas occurred at various times along the way. I have only listed the more interesting ones here. All this in the quest for the **original dream: power from pure rotary motion.**

Engine No 5. The Lissajoux Engine

Conception

Engine number five came as a result of my practice of bringing the latest rotary engine problem to mind when I get into bed each night. I have found this to be far more effective than counting sheep.

Exploration of an idea by rearranging or reconfiguring components is a normal technique. In this instance, I took engine No 1 and imagined what it would be like if the action were turned 90^0 to the central axis. The vanes would move horizontally, parallel to the central axis, in a cylindrical rotor. A series of curved chambers would be arranged, on each side of the rotor, in the endplates of the housing. The resulting two sets of chambers would reduce the size of an engine of a given capacity and lend it symmetry. The pressure of combustion would be contained by the housing and not transmitted to the main shaft. The sheep would have to wait. It is normally very hard to remember anything the next morning, but on the morning of the 23rd June 1997, number five appeared with impressive clarity.

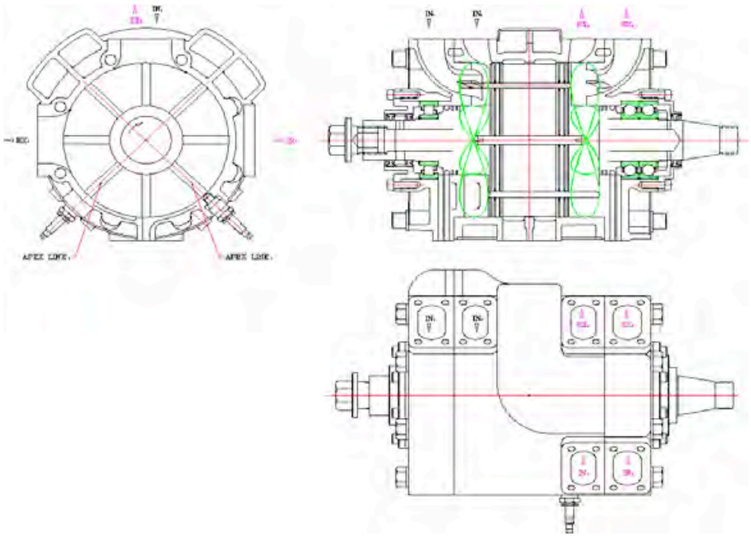
Principle

The assembly is composed of a cylindrical outer housing with a contoured endplate on each end. A rotating cylinder, with eight radial vanes situated axially around it, is mounted on a shaft with bearings in the endplates. The endplates have a sine wave contour, with two periods, arranged in a circle. This forms a lissajoux curve. The endplate lissajoux contours are disposed at 90^o to each other, on each side of the rotating cylinder. The necessary variation in volume is achieved by the reaction between the vanes and the wave contours in the end plates. The end plates are mounted on each end of the cylindrical outer housing. Inlet and exhaust ports are located in each endplate with two spark plugs mounted in the outer cylindrical housing.

This arrangement allows all four cycles of an Otto cycle internal combustion engine to be executed in one revolution. Eight vanes working in a set of chambers on each end means that there are sixteen combustion cycles each revolution. This is equivalent to a thirty-two-cylinder reciprocating engine. This would indicate a very smooth torque output. A preliminary design exercise was enthusiastically undertaken to explore the practicability of the idea.

Design

It is normal practice to attack a project of this magnitude in stages. The most important is: will it work? An engine with 1000cc capacity was chosen as a suitable size to demonstrate the principle. A simple 2D CAD design layout indicated that it might well be practicable. A more detailed 2D design layout was then commenced. This was the start of the real design procedure and helped resolve questions like: the general layout and overall size relationship, lissajoux curve excursion, compression ratio, port positioning, shaft and bearing sizes, lubrication method, cooling proposals and sealing techniques. This design layout gave enough detail to execute an evaluation of the worth this new engine against that of a reciprocating engine.



The preliminary Design Layout. Refer to Appendix **A-1** *Lissajoux Prelim.dwg*

Evaluation

A comparison between the proposed engine and a comparable reciprocating engine was undertaken to help appreciate the relative worth of the project. The comparison was direct and simplified. Friction was ignored and the varying pressures through the cycle were calculated using a Pressure Indicator Diagram. The torque utilized by the compression cycle was taken into account and is incorporated in the graph. This was a direct comparison using identical parameters for both the Lissajoux and reciprocating engines. It was intended as a comparison only and not an indication of absolute power output.

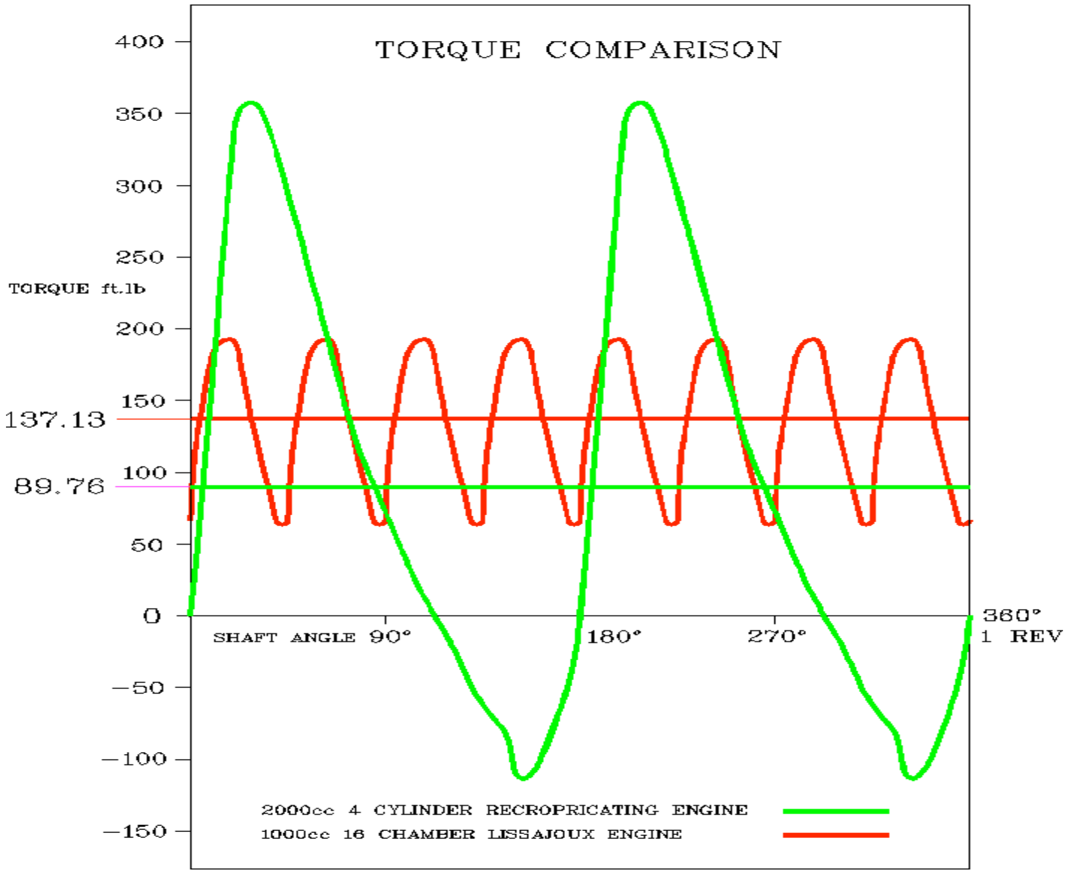
Comparison Method

The dimensions of the reciprocating engine were those of a Peugeot 505 which is a typical 'over-square' engine with a capacity of 1970cc. The pressures at the various crank angles were taken from an Indicator Diagram found in "The Internal Combustion Engine in Theory and Practice. Volume 1: Thermodynamics, Fluid Flow" by Charles Fayette Taylor. This is a graph of the actual pressure in the chamber of a reciprocating engine during the combustion and compression cycles. It reflects the complex set of conditions occurring during the various stages of the combustion and compression cycles. It is expressed in pounds per square inch of pressure against the variation in compression ratio. The exothermal heat generated as a result of combustion expands the gas and consequently expands the contents of the chamber. The temperature in the chamber is raised to about 1815^{o}C (3300^{o}F). The pressure generated at 8.75:1 compression ratio is about 4420Kilopascal (650psi). This pressure degenerates rapidly due to the heat absorbed by the components of the chamber, and as the volume of the chamber increases. Lowering the pressure of a gas, in itself, absorbs heat and consequently lowers the pressure further.

It was thought that a 1000cc Lissajoux engine should be compared with a 2000cc reciprocating engine because the reciprocating engine takes two revolutions to complete the four cycles and inducts 2000cc of combustible mixture in two revolutions. Consequently, a 2000cc reciprocating engine inducts 1000cc per revolution. The Lissajoux engine also inducts 1000cc per revolution but completes the four cycles every revolution. This would seem a reasonable basis for comparison.

The following diagram depicts a graph of the torque generated during one revolution of a 1000cc version of the Lissajoux engine, overlaid with that of one revolution of a four-cylinder 2000cc reciprocating engine.

A detailed drawing of the method of comparison is depicted in Appendix.A-2 *Lissajoux-Recip Comp.dwg.*



Torque of the Reciprocating Engine

The compression ratio was taken as the volume in the chamber, at any point, divided by the swept volume plus the combustion chamber volume. The compression ratio was then converted to pressure using the Indicator Diagram. This pressure was multiplied by the area of the piston to give the vertical force on the piston (p1). The force on the crank journal, transmitted by the connecting rod, was calculated as the Cosine of the angle between vertical and the angle of the connecting rod (p2). The force normal to the crank angle (p3) was calculated as the Cosine of the angle subtended between the angle of the connecting rod and a line normal to the crank angle. The torque was taken as p3 multiplied by the crank throw. This was a little tedious.

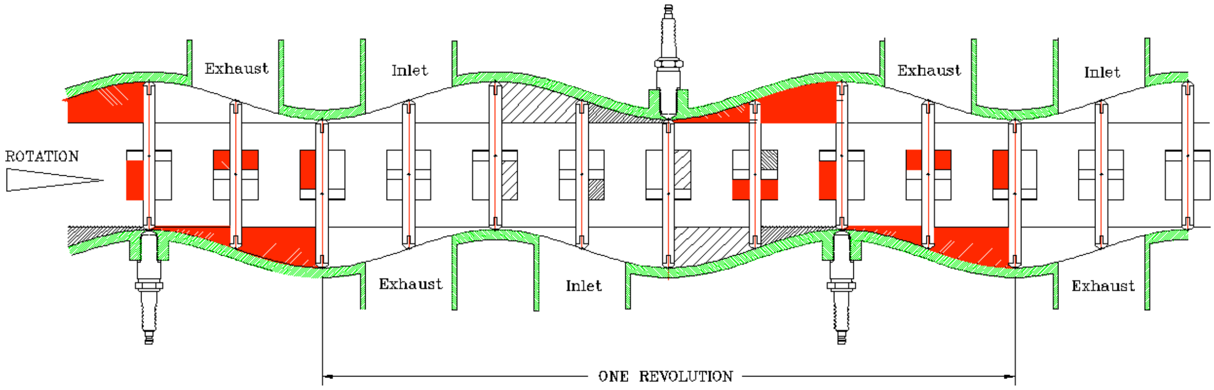
The method found to be more appropriate was to draw an accurate vector diagram of the cylinder, con-rod and crankshaft, in AutoCAD and 'list' the values of the various vectors. AutoCAD reported the vector lengths to an accuracy of four decimal places. The torque of the reciprocating engine was calculated at each 5^{o} angle of crank rotation from Top Dead Centre

(TDC) through the expansion cycle. This procedure was the repeated for the exhaust, induction and compression cycles. The vector diagrams for the reciprocating engine are depicted in Appendix **D-11** *6-1000 –Recip Comp.dwg*

The torque of the Lissajoux engine

The volume of the chambers of the Lissajoux engine at the various shaft angles posed quite a problem. The method used was to draw the endplate, vanes and rotor accurately, in AutoCAD as 3D solids, at the various required shaft angles. The chamber segments then isolated by subtraction and 'inquiring' the mass properties of each segment. AutoCAD reported the volume of each segment to an accuracy of eight decimal places of a cubic millimetre. The volume in each segment was converted to pressure using the Indicator Diagram. The pressure was multiplied by the effective area of the vanes, which was in turn multiplied by the average distance of the vane from the centre of the drive shaft. This was a reasonably complex exercise as there are normally two expansion and two compression cycles taking place at any one time in both the front and rear sets of chambers.

The following diagram depicts the sequence of events in an unwrapped, linear format.



Comparative Advantages

The **power/weight/size ratio** would be a significant advantage. The Lissajoux engine is about one-third the size and about one-third the weight of a reciprocating engine of a similar power output.

Improved fuel economy should be exhibited. The 1000cc Lissajoux engine would use same amount of fuel as a 2000cc reciprocating engine, but the graph indicates a greater torque output; 137ft.lb compared with 90ft.lb. This constitutes a potential 50% improvement.

Far less vibration and noise would be a valuable asset. The vanes are the only reciprocating components.

The graph indicates that the Lissajoux engine might give much **smoother torque** than an equivalent reciprocating engine.

Far fewer and smaller components would reduce production cost and material usage. Port induction and exhaust obviates the need for a valve drive train. Thus reducing the complexity of the engine.

Comparative Disadvantages

Sealing presents a formidable problem. As with all rotary engines, this proposal presents sealing as the crucial issue. Vane tip sealing is not the problem. But, the introduction of the pressure compensation flanges to the vanes introduced an additional requirement. The sealing required is straightforward. Nevertheless, it is additional and multiplied by eight vanes. All the sealing problems are solvable. It is their multitude, which constitutes the real problem. Each seal will leak, so the more seals there are, the more leakage will occur. The decision here is: is it worth it? The power \weight and the power/size ratio dictate that there is a niche market for an engine with these characteristics.

The **machining** of the lissajoux contour would require a specifically dedicated machine in production. This machine would require to be a four axis NC grinding machine.
The vanes reciprocate, and would require a reasonably complex pressure compensation system. The overall value of the project is predicated on this problem. A subsequent patent search revealed two engines of this general approach. Neither of them recognised that the pressure compensation of the vanes is a real problem.

Expectation

Overall, the project looked as though it might satisfy a niche in the market for a small, lightweight, high-powered unit. The project looks to be limited but enticing. The design proposal does not quite fulfil the ideal of ‘pure rotary motion’. Nevertheless, it appears worth pursuing.

Preliminary Design

Most of 1998 was taken up in designing the engine in detail. A 1000cc engine was designed using 2D orthographic CAD. This was the venue to determine the overall proportions of the engine. The first parameters to be determined were: the diameter and thickness of the rotor, the amplitude of the lissajoux wave, and the width and thickness of the vanes.

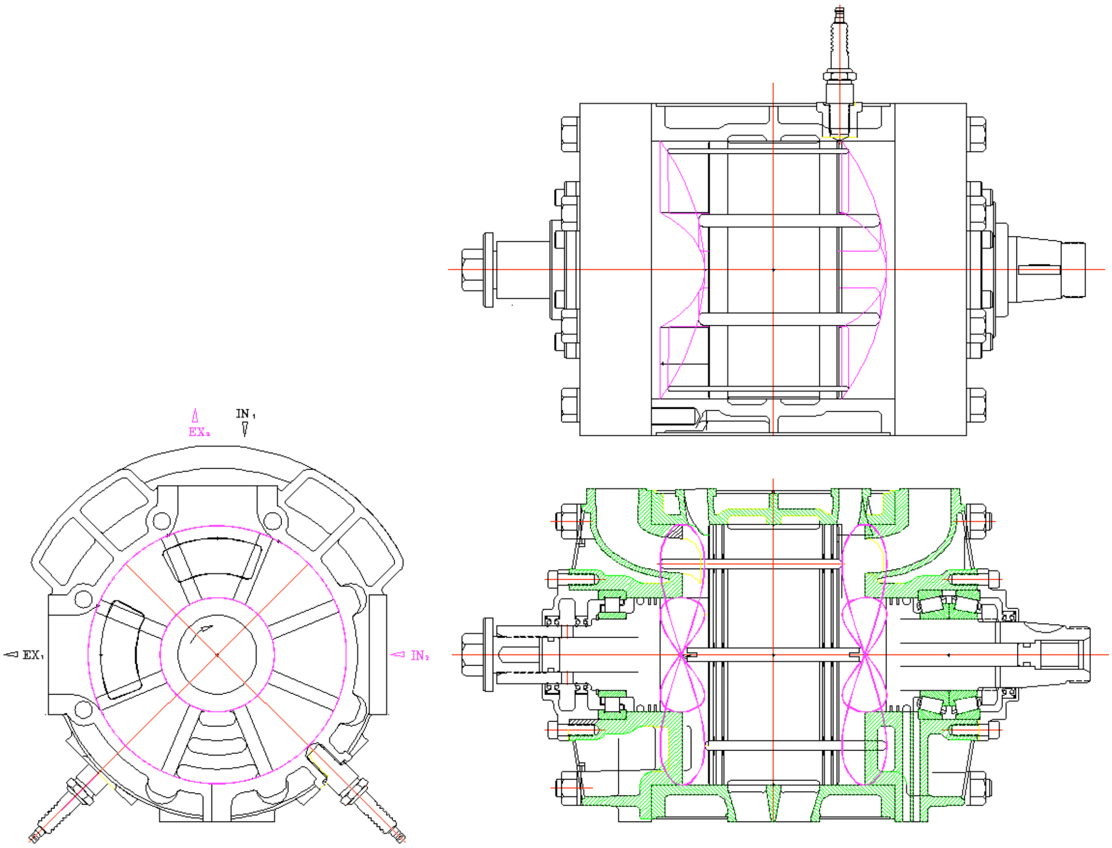
The preliminary design is depicted on page 45, for detail refer to Appendix **A-1** *Lissajoux Prelim.dwg.*

Detail Design

From this rather naive beginning, attention was then focused on the individual areas of design detail. The main items in this instance were: shaft size, bearing type and lubrication, cooling, fuel introduction, ignition and sealing. Each area demanded a deal of research. The following diagram shows part of the final design layout, which encompasses the information gleaned from the various research paths.

Overall Design layout of the 1000cc Lissajoux Engine.

For more detail, refer to Appendix A-3 *Lissajoux.dwg*



Shafts

The main shaft diameter was calculated, but the result was smaller than that used in the average 2000cc engine and as ‘prior art teaches’, a shaft size of 50mm diameter was chosen. Research among firms who have experience making similar shafts narrowed the choice to EN3327 steel, turned, case-hardened, to a depth of 0.7mm, with a subsequent fine grind. The material and processes were available and familiar.

Bearings

Control of end-thrust is a major factor in this engine. The combustion forces are axial and, under normal operating conditions, these forces are opposed and balanced. However, a malfunctioning sparkplug would impose significant end thrust on the system. The combination of an opposed pair of angular contact ball bearings on the output end, with a roller bearing on the left-hand end, would handle the loads with a considerable safety factor. The angular contact bearings would handle the end-thrust and the roller bearing would allow for expansion. The final choice was a matched pair of tapered roller bearings on the output end with a plain roller bearing on the left-hand end. This is overkill, however, on the basis that this is a prototype with a plethora of unknowns, an overkill in known areas was presumed to be reasonable.

Cooling

A water-cooled outer housing, barrel and endplates, with oil cooling for the shaft, rotor and vanes, was the choice based on the NSU-Wankel precedent. A combined water and oil pump unit would be toothed-belt driven from the front of the shaft. Two heat exchangers are necessary, one for the water and a second one for the oil.

Most of the heat is conducted away by the water as the housing absorbs the heat of combustion in two places continuously and the exhaust ports, which suffer the an even worse fate, need to be cooled as well. The combustion chamber formed by the rotor segments and the vanes are subjected to combustion heat through 90^o of each revolution. The rotor segments and vanes are also cooled by the freshly inducted air/fuel mixture. However, as the specific heat of oil is less than half that of water so both radiators would be the same size.

Fuel Introduction

This engine is able to be fitted with a carburettor, or be fuel injected. A single, a twin barrel or twin carburettors would be the simplest choice, though, a multi-point fuel injection system would give more control. In this case, simplicity is the choice. I have a brace of twin S.U. carburettors from a previous exploit, which will suit very well.

Ignition

One 14mm spark plug is fitted to bosses in the barrel for each bank of chambers. One is mounted in the front bank and one in the rear. They will fire simultaneously, eight times per revolution. For this reason, the heat rating of the spark plugs will need to be towards the cool end of the spectrum.

Two spark plugs, firing at a rate of eight times per revolution will be achieved with a high-speed electronic ignition system. The system comprises a HkZ101 hall-effect vane trigger, a programmable ignition computer, a multi-spark capacitor-discharge ignition unit and a dual-discharge coil. I built the programmable ignition computer from a kit No KC5202. This is a very high speed unit. It will handle the firing rate adequately. I built the CDI unit from a kit No KC5233. This unit delivers a spark, which borders on horrendous. I built the digital tachometer from a kit No KC3232. These kits are available from Jaycar Electronics.

There will be a notched timing flange fitted to the flywheel to activate the hall-effect trigger. The trigger transmits a series of pulses to the programmable computer and the digital tachometer. The computer adjusts the ignition timing according to need. The degree of adjustment is pre-programmable over three stepped revolution ranges. The advance and retard timing is continuously monitored. A diaphragm type vacuum sensing microswitch is fitted to the inlet manifold to sense throttle activation. The microswitch is connected to the computer.

The computer sends a series of timed low voltage pulses to a Capacitor Discharge Ignition unit. The CDI unit boosts the signal from 12 volts to 300 volts using a bank of capacitors. The 300 volt signal is transmitted to the primary connection of a dual-discharge coil. The dual-discharge coil is necessary because both spark plugs fire simultaneously.

Sealing

Sealing the combustion pressure has been a serious problem in rotary engines. In this instance, combustion pressure is expected to be about 650 psi. A reciprocating engine has circular pistons and bores. Circular sealing rings are easily manufactured, work extremely well and are very reliable. This is probably the main reason for reciprocating engines being as prevalent as they are.

Rotary engines tend to have straight seals with corner seals and many more of them. Straight seals work well over their length, however, each joint is a potential leakage point. It is the joints and the number of them, which presents the problem. The total length of the seals is also greater than in a reciprocating engine. A shorter seal length is obviously better.

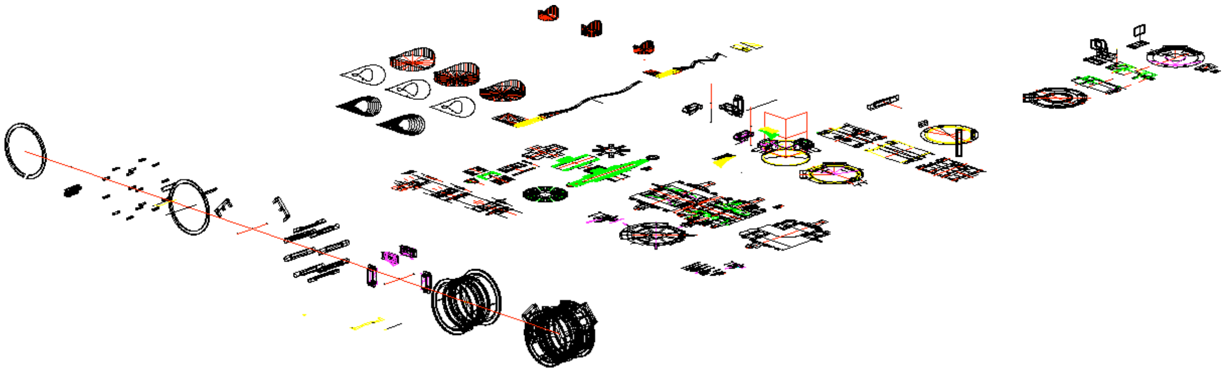
There is a design solution to each problem. The difficulty is to define the problem. Once a problem is recognized, the solution is merely a challenge.

Making

In this project, the design layout was drawn using the method outlined in Design Method and discussed on page 25. The details of each component were extracted directly from this design layout to individual drawings.

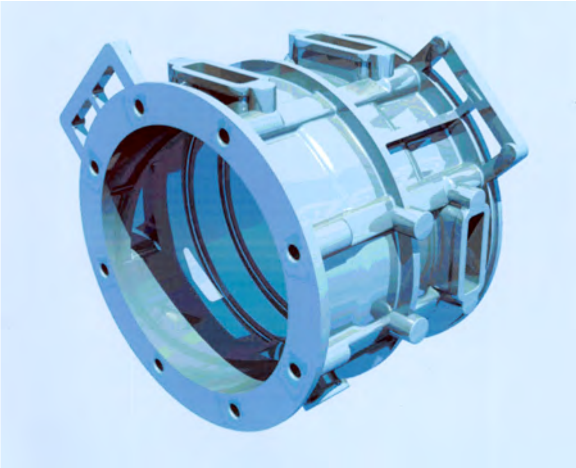
The 2D CAD information was expanded to 3D solid models and converted to steriolithography files. These files were then used to produce investment castings of the major components, such as the barrel, endplates and rotor segments. These 3D CAD models were constructed oversize with an extra 1.00mm machining allowance on the surfaces where machining was necessary. For the end plates, an additional 3D CAD model was required of the finished sizes. The endplates are complex enough to require to be produced on a four-axis 3D numerically controlled milling machine. This process requires the 3D model to be presented in steriolithographic format. This, in turn, is then converted, by the manufacturer, to machine language, normally Master CAM. It was also necessary to produce 2D orthographic drawings of the machining details of the barrel and rotor segment. It also became necessary for a number of other component drawings to be presented to the manufacturer as 2D orthographic drawings.

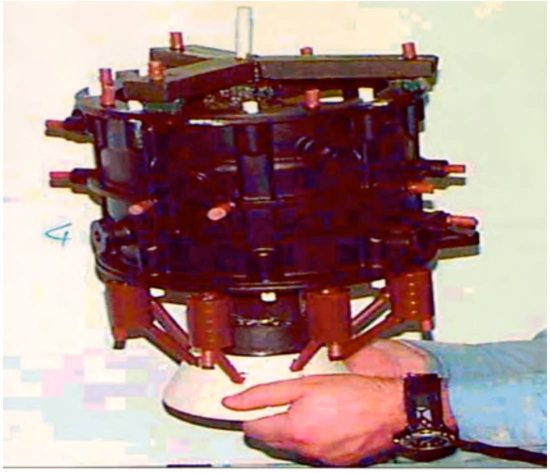
The barrel and endplates were produced using 3D CAD modelling from which, steriolithographic wax master models were generated. These wax masters were subsequently used to investment cast the barrel and endplates in SG400 cast iron. The eight rotor segments were manufactured by the same process, except that the material was phosphor bronze.
The barrel and endplate castings were designed so that the water jacket would be completed with the addition of 2mm thick brass cladding. This cladding was laser cut to profile, and was intended to be low temperature silver-brazed to the castings. The low temperature brazing is necessary because the critical temperature of the cast iron is 750^{o}F. At this temperature the crystalline structure of cast iron feels free to reorient itself and consequently the size and integrity of the part alters. The brazing material chosen was Eutectic Castolin 1020XFC. It has a flow temperature of 550^{o}F. Staying well below the critical temperature helps to obviate the crystal reorientation.



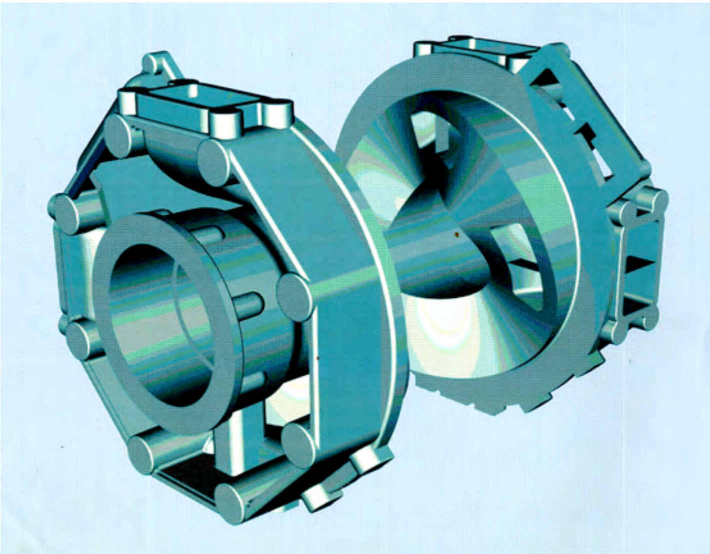
The final design layout and the detail drawings are viewable in Appendix **A-4** *Lissajoux Layout.dwg.* The 2D drawing of the Barrel is viewable in Appendix **A-5** *Lissajoux Barrel.dwg.*

The drawing above is viewable in Appendix **A-6** *Lissajoux 3D Barrel.dwg.* It illustrates the method that experience has taught me is a reasonable process when constructing a 3D CAD solid model and discussed in CAD in Design on **page 27**. This is the drawing of the Barrel shown in isometric view. The 2D design layout was developed first and individual aspects of the part were extracted, extruded into solids and oriented relative to a common datum point. This results in an array of the pieces, which can then be copied to another datum. I have found this the most convenient method for the reason that, although there is very rarely trouble encountered when joining the pieces, there is a great deal of trouble encountered when inserting the final filleting operation. Nearly all corners and edges need to be filleted to impart strength to the final part. If corners and edges are left sharp, internal and external stress will cause the part to fail. Inserting the fillets is usually left until the final assembly because it is almost impossible to anticipate which order of amalgamation will result in successful filleting.


3D CAD model of the Barrel



Investment Casting 'Tree' of the Barrel



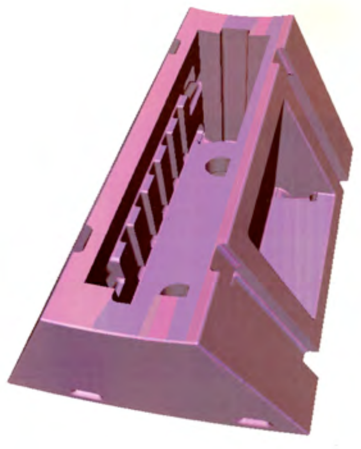
3D Model of the Endplates

The 2D drawing of the Endplate is viewable in Appendix **A-7** *Lissajoux LH End.dwg*.

The 3D drawing of the Endplate is viewable in Appendix **A-8** *Lissajoux 3D Ends.dwg*.

Detail of the shaft and hub are viewable in Appendix **A-9** *Lissajoux Shaft-Hub.dwg*.

Detail of the vane is viewable in Appendix **A-10** *Lissajoux Vane.dwg.*



3D model of the Segment

The 2D drawing of the Segment is viewable in Appendix **A-11** *Lissajoux Segment.dwg*.

The 3D drawing of the Segment is viewable in Appendix **A-12** *Lissajoux 3D Segment.dwg*.

4

The Hudson Five-Cycle Engine

Conception

In November 1998, I hurt my back moving a massive boulder in the garden. There were no interesting magazines in the doctor's waiting room, so I closed my eyes and brought up the rotary engine on the inside of my forehead. This time I went right back to basics, **the original dream**. It all fell into place. "I can do that!". No 6?

All engines and compressors need a differential area between an active and a reactive element. The simplest rotary manifestation of this, other than a reciprocating machine, is the Watt rotary steam engine. Refer to *On Rotary Machines. Diagram 2.* The Watt engine would require an additional compression stage with a remote combustion chamber to work as an internal combustion engine. This is where I started.

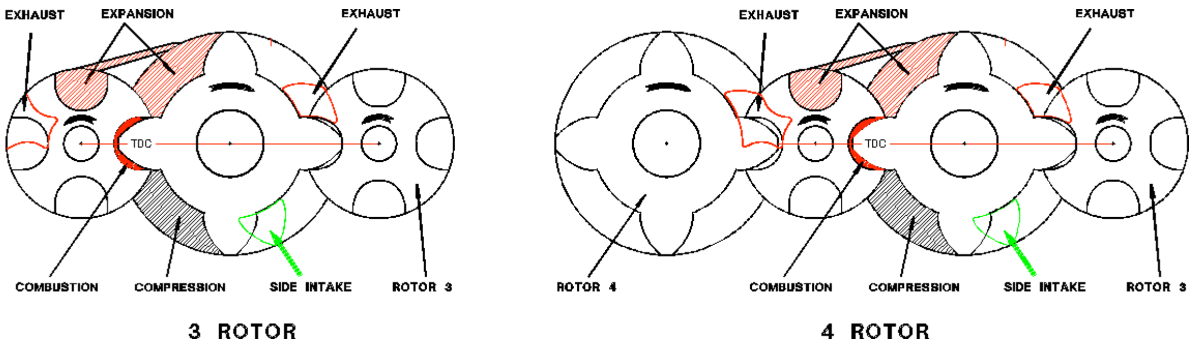
What I was searching for was: a single rotor device, able to induct a fresh air/fuel charge, compress it into a combustion chamber, ignite it then utilize the expansion against a reactive element to produce torque and then exhaust the burnt gas. All this should happen in one revolution.

The main problem was to devise a suitable reactive element. The simplest single shaft device that I have met is my own engine No. 2. Refer to Prior Hudson Engines. However, if a second interactive rotor were added as the reactive element it would look like the compressor profiles I developed for the axial flow screw compressors in 1970 and 1993. Back then, I had drawn the diagram of the new engine about twenty times as a screw compressor without realizing its possibility as an engine.

The original profiles were intended to be extended in a helical form, so that the compressed gas is forced axially along the helical screw and into an exhaust port at the far end. However, if the same profiles were straight cut, they would satisfy the present requirement nicely. The charge could be compressed between the male tooth and a slightly enlarged female cavity profile. The amount of this enlargement would determine the compression ratio.

The initial manifestation of the thought was to be a normal 4 stroke Otto cycle which fires every revolution. It would be completely rotary, with no reciprocating parts. The first design had three sets of shafts and rotors. The third shaft and rotor was to purge the burnt gas from the chambers in the male rotor and induce a fresh charge. A fourth shaft and rotor would be required to purge the chambers in the female rotor. This would be very unwieldy.

The diagram below shows the initial manifestation of the idea using a ratio of 1:1 with 4 teeth. For a drawing showing an investigation of 2, 3 and 4 teeth, refer to Appendix **B-1** *6-1.dwg.*



This was obviously not a very productive design direction. There was none of the satisfaction quotient mentioned in 'Creativity' in Appendix 1. This lack prompted further exploration.

In the three rotor diagram, the left-hand rotor is the active female rotor, and after exhaust, a full chamber of burnt gas remains. To purge this gas a forth rotor would be necessary. However, the relevant chamber in the fourth rotor would still contain burnt gas. Not satisfactory! Two rotors would be the preferred configuration. Having come to this realisation, I constructed a two rotor construct in my imagination and proceeded to rotate them. It became obvious that there was excess rotation during which nothing was happening. I could also visualise that, if this space had an additional port in the main housing it would allow this volume of gas to be centrifugally discharged outward. The second realisation was that if there were two further side ports, open to atmosphere, in the endplates, close to the root diameter of the rotor cavities, fresh air would be drawn in to replace the burnt gas centrifuged into the exhaust port. Both rotors become fresh air pump for a significant portion of each revolution. It would also constitute an additional fifth phase into the power cycle. Two rotors have now become a reality. This is a direct example of following the approach to design discussed in Creativity, Imagination, Concentration, Commitment and Incentive in Appendix 1. The satisfaction quotient was eminently satisfied.

The next sage was to design this new engine and evaluate its potential.

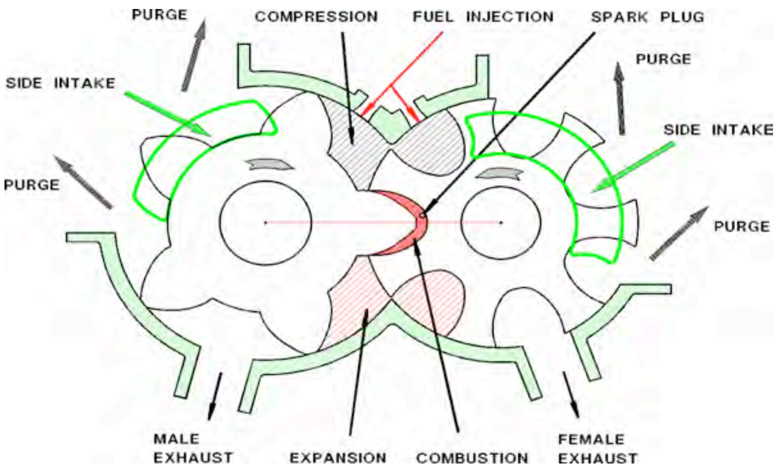
The Five Cycle Engine

The fifth phase would require more chambers to allow all five cycles to be enacted in one revolution, however, having a larger number of chambers would also produce a smoother torque output.

Preliminary investigation indicated No 6 to be an improvement over No 5 in several important aspects. No 6 has a pure rotary action. In No 5, the vanes have a reciprocating movement. No 6 is smaller and simpler than No 5 for a given capacity.

Principle

Two rotors are fixed to two shafts with a pair of timing gears to maintain synchronization and prevent rotor clash. The rotors each have a particular profile and interact with each other in a



similar fashion to a pair of spur gears. The rotors are enclosed in a binocular shaped main housing with two endplates. Two bearings in each endplate carry the shafts. The main housing has two exhaust ports and two purge ports. Inlet ports for both the male and female rotor cavities are located in the endplates. A spark plug is located in each endplate.

As the rotors rotate, air is trapped in the cavity formed by the male tooth and the female recess and is compressed. Fuel is injected during the early stage of the compression cycle. Maximum compression is reached when a tooth of the male rotor is aligned with a recess in the female rotor. A spark plug is located at each end of the compression cavity and fire simultaneously at the appropriate time. Ignition of the air-fuel mixture causes the expansion of the gasses to raise the pressure in the cavity. This rise in pressure forces a reaction between the rotors. The tooth on the male rotor reacts against the recess in the female rotor, which imparts torque to the male shaft. The female rotor is the reactive element and does not contribute torque. The cavity formed by the rotors expands as rotation progresses until maximum volume is reached. At this stage, the cavities in the each rotor reach an exhaust port in the main housing and the residual pressure in the cavities is released into the exhaust ports.

However, the cavities still contain burnt gas. As rotation progresses, the cavities in both rotors each reach a purge port in the main housing. These purge ports are quite long and large. The remaining burnt gas in the cavities is centrifugally thrust into these purge ports. The male and female cavities then reach inlet ports in the endplates, which admit clean air. The centrifugal action of the burnt gas moving radially outward, draws clean air into the cavities through the inlet ports in the endplates. This purging of the male and female cavities constitutes a fifth cycle over and above the normal Otto cycle of intake, compression, expansion and exhaust. The cavities then pass the end of the purge and inlet ports. The clean inlet air is confined by the main housing and the compression cycle recommences.

All five cycles are happening simultaneously, and each pair of cavities fire every revolution. Two expansions and two compression cycles occur concurrently for 30^{o} of rotation for each cavity.

This new proposition promises to constitute a smooth running, low-vibration and more efficient means of power production with excellent power/weight and power/size ratios.

Case Study 1: The Design of a 1000cc *Water-Cooled* 5 Cycle Engine, 5:7 Ratio

Design Exploration – Refining the Profile

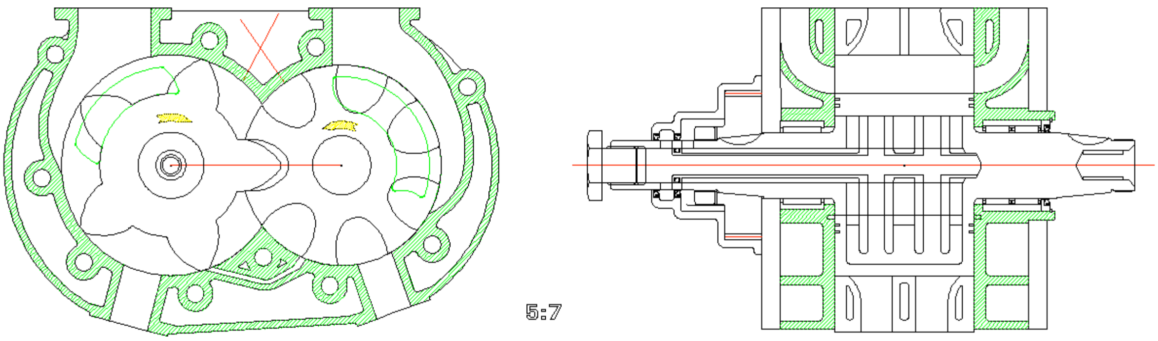
The profile could be illustrated as the path described by the locus of one rotor as it intrudes on the other. The larger rotor assumes a male, or convex, profile while the smaller adopts a female, or concave, contour. A pair of profiles is acceptable when there is no overlap or undercut in the male profile and the female tooth is wide enough to allow internal cooling cavities. There are many acceptable ratios. The ratio, number of teeth and maximum tooth depth are interdependent factors.

Ratio Investigation

The next exercise was to explore the factors controlling the various gear ratios, and number of teeth, which might prove practical for this application. The larger rotor is always the male.

A larger number of teeth are required to fit all five cycles into 360°, while a lesser number of teeth, allows a greater tooth depth and simplicity.

For detail diagrams of investigation into various ratios refer to Appendix **B-2** *6 Ratios.dwg.* This exercise showed the most promising ratio to be 5:7.



Part of the preliminary design of an engine of 1000cc capacity at 5:7 ratio

A more detailed version may be viewed in Appendix **B-3** *6-57.dwg.*

The 1:1 Ratio

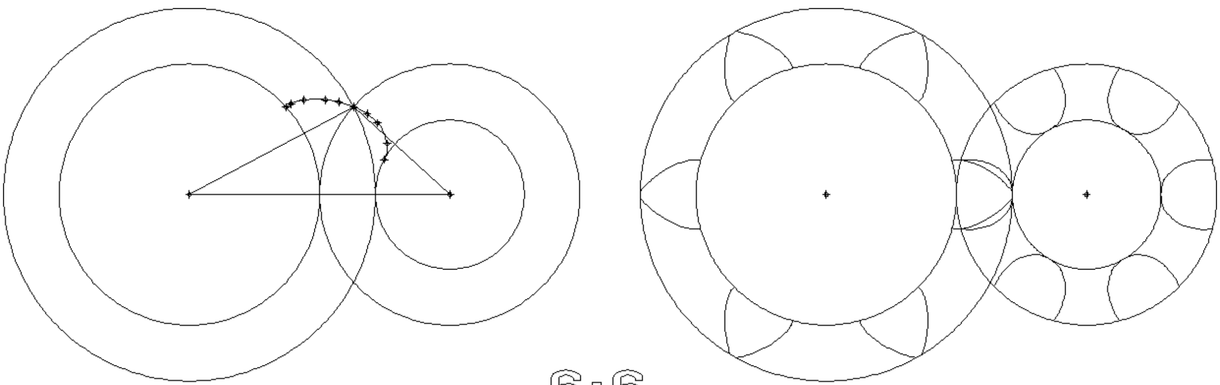
The 5:7 ratio is practical, however, the 1:1 ratio investigated in 1994 was revisited again in 1999. Revisited, this time because the simplicity of 1:1 calls on a basic aesthetic appreciation.

In addition, as with any design proposal, it is possible to sense when a satisfactory solution has been reached. 5:7 did not quite give enough of this sense of satisfaction. Investigation of various possibilities should continue until gratification is gained.

The main factor involved is the width of the female teeth at their narrowest point. This is governed by the number of teeth in the female rotor, relative to diameter and tooth depth. Therefore, a larger diameter female, proportionate to the male, seemed to be indicated. I had also harboured the concept that the rotors should be as close to equal size as possible. This was a hangover from having originally developed the 2:1 profile back in 1970. The 2:1 ratio allows equal diameter rotors: very satisfactory as a screw compressor, but not applicable as an engine. In addition, as the ratio approaches 1:1, the female diameter reduces relative to the male diameter. The female tooth width is governed by the tooth depth. A larger number of teeth demands a smaller tooth depth for a given diameter. For this reason, 1:1 seemed to be unsatisfactory. 1:1 still had an appeal that I could not ignore.

At this point, I decided to abandon all my preconceptions and let the female, with a reasonable tooth width, determine the factors governing the proportions of 1:1. The male diameter was quite large to my eyes, but six teeth did seem to be practicable. It took about two minutes to allow a rational interpretation to the larger male diameter. If there must be two rotors, it would be better if one of them had as little mass as possible. A larger male root diameter would allow freedom of choice of the main shaft size. A reasonable tooth depth and width was practicable. The elusive 1:1 a reality at last.

The following diagram shows the method of profile development and the preferred proportions.



6:6

Various numbers of teeth at 1:1 may be viewed in Appendix **B-4** *6 No of Teeth.dwg***.**

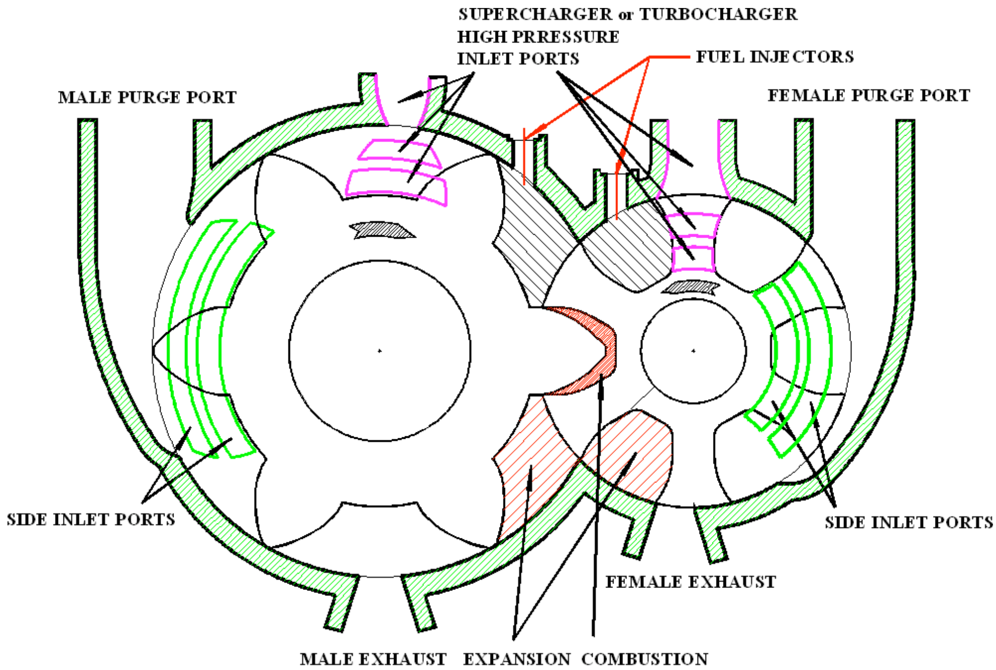
The 1:1 ratio looked to be practical with six teeth in both the male and female rotors. Six teeth would allow a longer purge cycle. The female tooth width appeared satisfactory and the root diameter is large enough to permit suitable shaft size and end sealing. 1:1 with six teeth needed refinement, but was now adopted as the final solution with an immense sense of satisfaction.

Turbo-charging and Supercharging

Five teeth are the minimum necessary for a normally aspirated engine. If a turbo-charger or supercharger were to be fitted, six or seven teeth would be necessary, as the fifth cycle would need to be shortened to prevent the pre-compressed air entering during the purge stage. An additional sixth stage with two inlet ports, just prior to the commencement of the compression stage would allow separate admission of the pre-compressed air. This separation of the high pressure inlet from the purge phase would allow fitment of either, carburation or multi-point fuel injection, to the inlet side of the supercharger or turbocharger. These are alternatives to the present fuel injection direct to the chambers during the early stage of the compression cycle.

A very useful attribute of both the 5 Cycle and the 6 Cycle versions is that exhaust back-pressure does not affect the torque output of the engine. This makes it ideal for turbo-charging and allows fitment of a more complete silencing system.

The following diagram illustrates the 6 Cycle version.



Supercharged or Turbocharged Engine: 6 Cycle - 6 Teeth

Curve Investigation

This profile has been utilized in screw compressors but is merely called a 'Generated Profile'. With the previous engine being based on a 'Lissajoux' curve, 'Generated Profile' did not seem to be worthy. I have named this particular generated profile 'Pro-cyclic'. This name is based on 'Pro' meaning external or outside, and 'Cyclic' meaning a figure having a circular aspect. In this instance, there are two interacting circular elements with the central axis of each element external to the other.

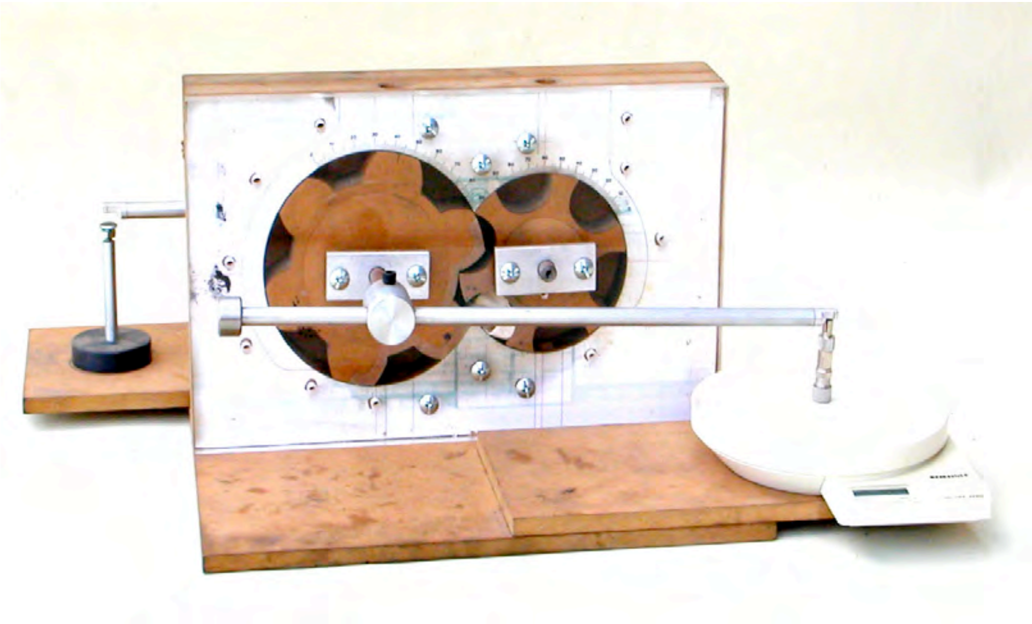
Torque Test

A battle ensued in my mind as to whether the female rotor would contribute torque. I was able to rationalize that it did. Then, taking the devils advocate role, I was able to resolve equally well that it did not. In order to resolve this quandary, I designed and built a test rig. It was also designed to test the proposed torque output of the male rotor. Refer to Appendix **B-5** *6 Test Rig.dwg*.

It was a sandwich construction made from 30mm thick MDF with a 12mm thick acrylic front panel. The rotors are each fixed to 12mm diameter shafts, which are mounted in bearing plates front and back. A 1ft lever is attached to each shaft to transfer the torque to digital weight scales. A bladder was inserted into the gap between the male and female and a pressure-regulated supply of oxygen at 10psi was introduced through a pintle. The bladder exerted pressure in the cavity between the male and female teeth. The resultant torque exerted by the male and female rotors was taken at a number of rotor rotation angles from top dead centre. The tests were repeated using 15psi.

The original question was immediately resolved. The female rotor does not exert torque. Knowing the answer, the reasons were obvious. The devils advocate reasoning was correct. The pressure exerted on the female is absorbed in all directions equally, and is transferred radially to the shaft. The female geometry does not constitute the necessary offset. So, no torque is exerted by the female rotor.

The male rotor obtains an offset from the female rotor and does transmit torque to the main shaft. This series of tests was not able to corroborate the anticipated torque values, as it was not possible to insert the bladder into the fine gaps in the cavity. This meant that the pressure was not exerted over the total tooth area available to gas. Refer to Appendix **B-5** *6 Test Rig.dwg* for a detail drawing of the test rig and the results.



Case Study 2: The Design of a 1000cc *Water-Cooled* 5 Cycle Engine, 1:1 Ratio with 6 teeth

Preliminary Design

There were many unknowns at this point. The next step was to undertake a preliminary design layout using 2D CAD to establish a first pass effort to determine the general size and shape of the components of the engine. Various factors were investigated. Refer to Appendix **B-6** *6 Prelim.dwg.* It became obvious that an in depth study of the effects that the variable factors would have on the practical behaviour of the proposed engine.

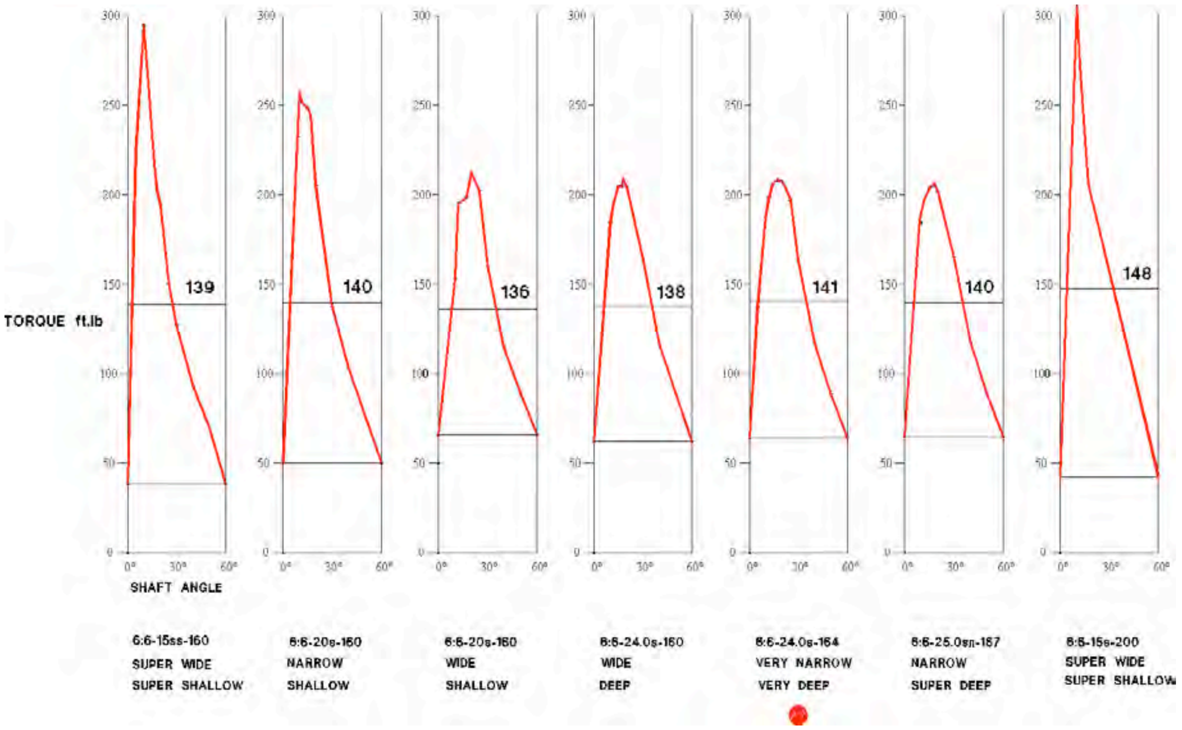
Proportions of a 1000cc Engine

The main question in my mind was the effect that various diameters, tooth depths and widths have on the overall characteristics of the engine. The only way to resolve this question was to develop profiles of various diameters and tooth depths and compare the graphs of the anticipated torque output for each. I had no idea how exhaustive and patience absorbing this exercise would be when I started. It was imperative, though, and was done.

AutoCAD was used in 2D mode to develop the profiles. This was the most convenient method available to accurately obtain the areas needed to establish the rotor lengths and the effective tooth areas and vectors.

1000cc was the capacity common to all the configurations. The major diameter of the male rotor was the basic parameter. The male rotor diameters varied from 150mm to 200mm with a number of tooth depths for each diameter. The tooth depth influences the pitch between the rotor centres and consequently the overall length of the rotors.

The following series of graphs show the results of the comparison exercise.
Refer to Appendix **B-7** *6 Proportion Investigation.dwg* for the complete coterie.



The pressure and torque calculations were based on $P_1.V_1=P_2.V_2$ rather than an indicator diagram as the compression ratio had yet to be determined and this was intended as a comparison exercise only, not an indication of eventual performance.

The comparison procedure indicates that the torque output does not vary much over a variety of configurations. It also shows that a wide shallow tooth produces a very high peak early in the cycle. This is not a desirable trait. It is far more advantageous for the torque curve to be as flat and smooth as possible. As a basis for development, the obvious choice, was a profile with a male diameter of 164mm, with a narrow male tooth tip and having as large a tooth depth as possible.

The exercise was very laborious but it was essential ground breaking work and completing it was very gratifying and a huge relief. It is also nice to know that it will not need to be repeated in the future.

General Approach

The Lissajoux engine castings were expensive, so I thought it might be a reasonable idea to design the engine using more basic construction methods. This design would incorporate construction methods like fabrication for the main housing and patternmaking for the endplates in lieu of steriolithography and investment casting. These methods would reduce the cost significantly, but would increase the time that I, personally, would need to invest in the project.

Design

The beginning of a new is exciting. The unknown beckons. I have outlined the approach I take when confronted with these unknowns in ‘Design Method’ in Appendix 1. This project is an applied example of that process.

In this case the starting point was the profiles of the rotors. These were established during the proportion exercise. The profiles automatically set the rotor length. The next step was to make an initial attempt to establish the timing of the five cycles. Drawing in the first pass at the port sizing and position helped solidify the overall layout. It was still fluid but was gaining solidity. Adding cooling, lubrication and air and fuel induction began to impart a degree of reality.

It was to be of sandwich construction having the main housing in the centre with the two endplates either side of it and two 12mm aluminium plates on each end of this. There was to be a cast aluminium timing gear cover on the output end and another cast aluminium oil input manifold on the other end. The whole sandwich would be tied together with twelve high tensile tie-bolts.

Detail Design Layout

Cooling

The main housing and endplates were to be water cooled with the shafts and rotors, oil cooled. This would require an external water/oil pump unit. This would be a dual centrifugal type unit delivering low-pressure water and oil separately.

The Main Housing

The main housing was designed to be fabricated from bright mild steel. The method of manufacture was to roll two 10mm thick tubes allowing a 1.5mm machining allowance. These were to be turned to size on their outer diameter, then cut and scarf welded to form the binocular shape which was to form the basis of the housing. Three 10mm plates were to be laser cut to profile. A series of spacer blocks were to be shaped. Then the whole collection was to be welded to form the main housing assembly. The assembly would then be machined and the inside surfaces case hardened and ground.

The Endplates

The endplates were designed to be cast in SG400 cast iron. The design was slightly restricted, in that the pattern was to have 2^o per side draft without cores or inserts. This caused a thickening in the spark plug mounting area and the outer walls and inner flanges where water sealing against the aluminium plate was required. This would add weight but is much simpler to build. Additional weight in the prototype was not considered to be a major factor.

The Rotors

The rotors were to be investment cast in SG600 cast iron off wax models produced from steriolithography masters. This was necessary as the detail of the internal coring for the oil cooling was quite complex. To produce the castings from patterns would require complicated core boxes. The rotors were to be bored to be a shrink fit onto the shafts.

The Shafts and Timing Gears

Because of space restrictions, it was decided to use needle roller bearings running directly on the shaft without an inner race. In order to accomplish this, the shafts were to be manufactured from EN3327 steel, case hardened 0.75 deep to 62 Rockwell C and then fine ground to very fine tolerances.

The timing gears were to be fixed to splines on the output end of the shafts. They were to be helical at 14^o to reduce noise and to provide a fine degree of adjustment of the rotor orientation by shimming.

The Manifolds

The exhaust manifold would need to be constructed from stainless steel because the exhaust is almost continuous. This means that the exhaust manifold will run at very high temperature. The manifold plates would be laser cut from 8mm thick stainless steel. The manifold itself would be formed from laser cut 2mm thick stainless steel and TIG welded.

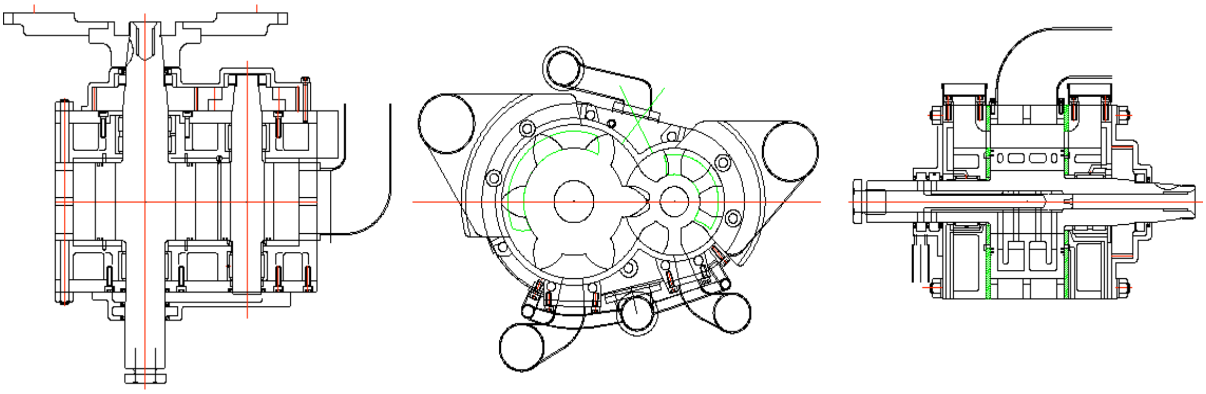
The purge exhaust manifolds (the fifth cycle) would be fabricated from 1mm thick mild steel by the same method.

The inlet system would be constructed in much the same manner except for the throttle assembly which would be turned from aluminium and fitted with a sealed bearing mounted butterfly.

The cooling-water, inlet and outlet, manifolds would be bent tubing welded to laser cut plates.

The following diagram is a partial view of 6-1000 Water.dwg

For a more complete view refer to Appendix **B-8** *6-1000 Water.dwg*.



Case Study 3: The 28cc 5 Cycle Engine

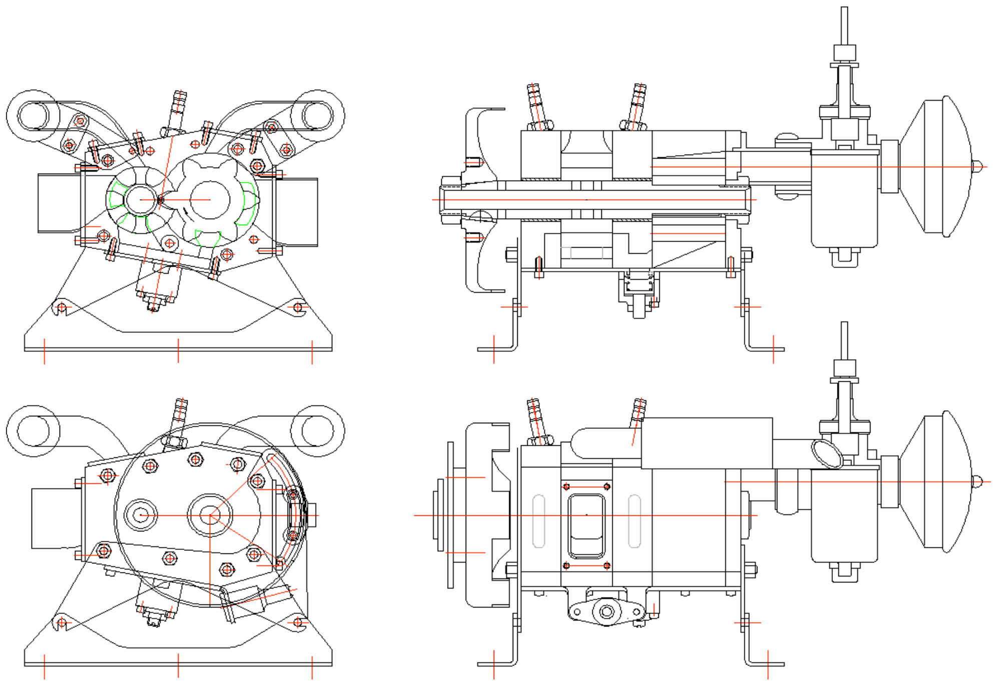
General Aim

I was relatively pleased with this 1000cc design, but I rationalized that the cost of building it would be roughly equivalent to the money spent on the Lissajoux engine. The cost of a repeat of that magnitude would be a little too much for me at that time. I reasoned what was needed at this point was an engine, which merely worked well enough to demonstrate the principle. The minimum to achieve this reduced aim could be similar to an oversized model aircraft engine. The size decided on was 24cc. In order to demonstrate the principle only, cooling would not be necessary, as the proposed running time would be quite short. A small engine, like the one contemplated, could have plain bearings lubricated by adding oil to the fuel. Sealing would be affected by close running clearances.

Design

The design of a simplified 24cc engine was undertaken. The emphasis was on simplicity. It is composed of four aluminium blocks machined to very fine tolerances, doweled and clamped together with tie-bolts. The rotors were to be 'wire cut' in profile and low temperature silver-brazed to the shafts. The engine would to be fitted with a carburettor, as fuel injectors are not available, small enough to suit this engine. To offset this discrepancy, it was though that, if the timing gears were made longer with a coarser pitch diameter, they could be utilized as a supercharger. A detail design layout was completed in 2D CAD using a large portion of the research done for the 1000cc design. In order to utilize convenient material sizes the final size of the engine was 28cc. The following diagram is a portion of the design layout 6-28.dwg.

For more detail refer to Appendix **C-1** *6-28 Layout.dwg.*



Making

The design layout was drawn, in fine enough detail that detail drawings of the individual components could be extracted directly to become working or part drawings. Refer to Appendix **C-1** *6-28 Layout.dwg*.

The shafts and timing gears were manufactured by Hardman Bros. I subsequently lapped the gears to a fine running fit, as minimum backlash was required. This set the centre distance and consequently the final profiles of the rotors could be generated. Detail of the layout may be viewed in Appendix **C-2** *6-28 Gears-Shafts-Nuts.dwg.*

I thought the rotors would need to be at least air-cooled. With this in mind, I designed them to be wire cut from mild steel plate in layers with the cooling ducts incorporated in the layers. An allowance was added on the outer profiles so that after the plates were brazed, in an inert-gas furnace, the final profiles could be finely finished using wire cut with a triple passes of the wire. This would result in a extremely close approximation of what was necessary. Details of the wire cutting profiles are shown in Appendix **C-3** *6-28 Wire Cutting Profiles.dwg*. I manufactured two compression jigs for the brazing process. Details of the Copper Brazing Jigs are shown in Appendix **C-4** *6-28 Brazing Jigs.dwg.* Unfortunately the brazing firm did not use enough bronze powder. The whole exercise was ruined. Rather than repeat the whole episode, I decided to eliminate the cooling of the rotors. This would reduce running time but would allow the rotors to be wire cut from one piece. This was done and they turned out very well.

The spark plugs were mounted in the bearing blocks and had to penetrate a goodly distance down to the combustion chamber. This made them unique. I designed a specific spark plug using 6.1mm diameter alumina ceramic tubing with a 1.8mm steel electrode cemented in place with high temperature alumina ceramic adhesive.

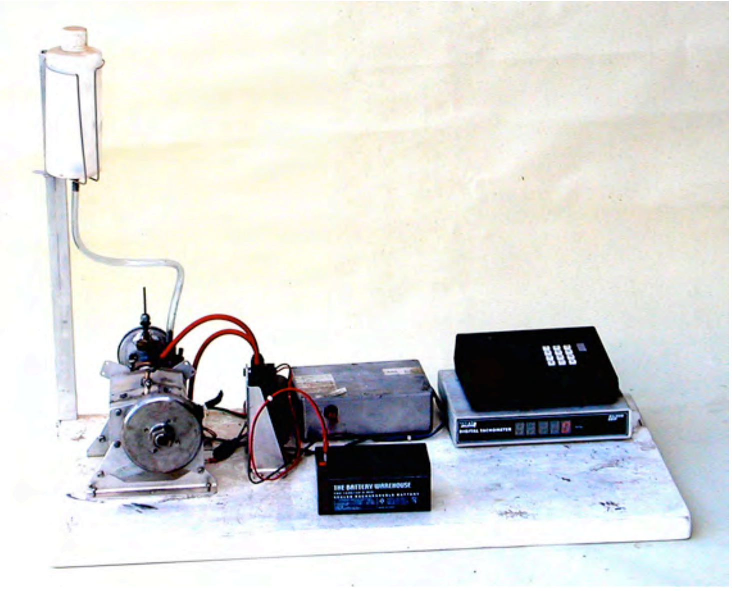
The five blocks: two bearing blocks, the main housing, the timing gear housing and the timing gear cover plate, were then milled and the bearing blocks were fitted with phosphor bronze bearings. Detail drawings may be viewed in Appendix **C-5** *6-28 Blocks 123&4.dwg*, **C-6** *6-28 Spark Plug Hole.dwg*, **C-7** *6-28 Block 5.dwg*, **C-8** *6-28 Relief Valve.dwg* and **C-9** *6-28 Tapped Holes.dwg.* The person who machined the blocks is a very good machinist but I think he gave my job to the apprentice. They did not turn out very well at all. I spent a great deal of time remaking the dowel pins and refitting the blocks. To no avail, as it turned out. I was able to control the end clearance by lapping the blocks but the diametral clearance was excessive. I did not hold much hope. However, at this stage, it was worth trying.

Test Series

A test platform was designed and built.

For details refer to Appendix **C-10** *6-28 Test Platform.dwg.*

The engine was mounted, and the ignition components, built for the Lissajoux engine, were installed. I decided to fit a manual advance and retard mechanism in order to establish the various advance and retard settings prior to connecting and programming the computer.



Test sequence

Test 1. The initial attempt to start the engine was at 8.00 PM 14/10/00. The fuel was model aircraft mix with 10% nitro added to give it the maximum chance of igniting. This was on the eve of presentation at the autumn Graduate Research Conference in the School of Architecture and Design. An attempt was made to start the engine at 650 RPM. Various advance and retard settings were tried. It did not start. I tested the neighbours noise tolerance without result.

Test 2. The next trial was the following day at the Graduate Research Conference at 2.00 PM on 15/10/00. Once again it did not start. During the attempted demonstration it caught fire but was easily extinguished. At least this indicated that the CDI unit and spark plugs were operating.

Closer inspection revealed that the ignition system was not working properly. The timing socket had been damaged in transit. The timing socket was repaired. Carbon deposits on the spark plugs indicated that the spark pugs were working and that combustion had taken place.

Test 3. An attempt was made to start at 850 RPM at 5.00 PM 21/10/00. It failed to start. I stripped the engine. There was further evidence of combustion having taken place. Both the side and radial clearance were excessive. There was also more backlash, in both the main rotors and the timing gears, than I would wish. The sealing was seriously compromised. I suspected that there was very little compression. Repair of both these defects was possible by hard chrome plating the meshing surfaces of the rotors.

Test 4. In order to test the compression, I made a pintle with a pressure gauge connected. This was fitted in place of one of the spark plugs. At 850 RPM the indicated pressure was 20 psi. Absolutely abysmal. This is just enough to allow mild combustion but not nearly enough to generate enough pressure to overcome friction.

Closer inspection revealed a more serious problem. The supercharger was not delivering the charge to the right place. To correct this, the porting would need modification and two additional ducts would need to be added.

Conclusions

These modifications could be attempted, but working on the 28cc engine was like working on an internal combustion watch. The small physical size of the components demanded a degree of precision that was not within my resources to implement. The end result would still be less than I had hoped to achieve.

This was exceedingly disappointing and constitutes a minor tragedy. It is here that a demonstration of the perseverance discussed in ‘Commitment’ in Appendix 1 needed to be demonstrated.

Acting on this provocation, I decided to raise my sights again and return to the original intention: to build a 1000cc prototype. The larger size would contain all the design elements that were eliminated in the small engine. The clearances would be the same but in the larger scale engine the relative clearances would be much more realistic. All the elements missing in the smaller attempt could be incorporated in the larger version. The main ones being spring loaded sealing elements, cooling and lubrication. I decided to shelve the 28cc version for the time being and complete the design of the 1000cc then build a working prototype.

The 28cc version will be revisited at some time in the future.

Case Study 4: The Design of a 1000cc 5 Cycle *Oil-Cooled* Engine, 1:1 Ratio with 6 Teeth

General Approach

I turned my attention back to the design layout of the second iteration of the No.6 1000cc engine, which utilized the less expensive construction methods.

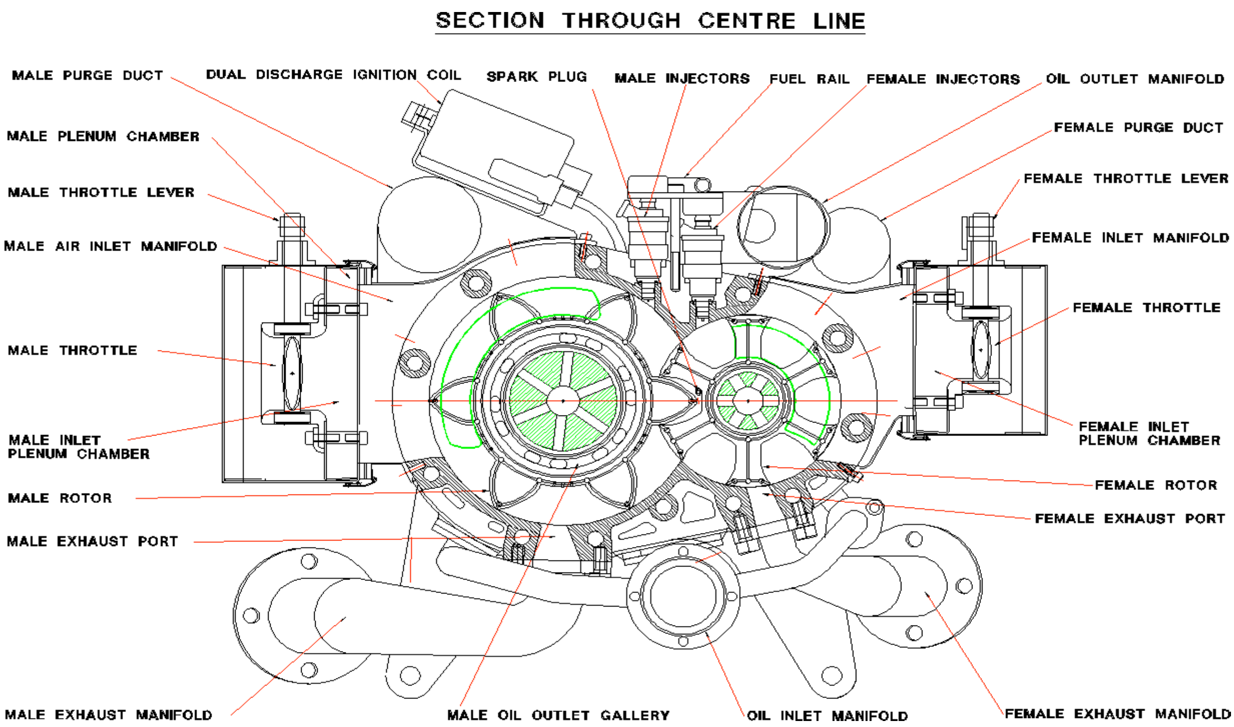
While reacquainting myself with the design layout, I was struck with how much simpler the layout would be if the main housing was to be oil cooled. Oil has a specific heat about half that of water. This would mean twice the throughput. Even so, the engine would run hotter. But the advantages might offset this disadvantage.

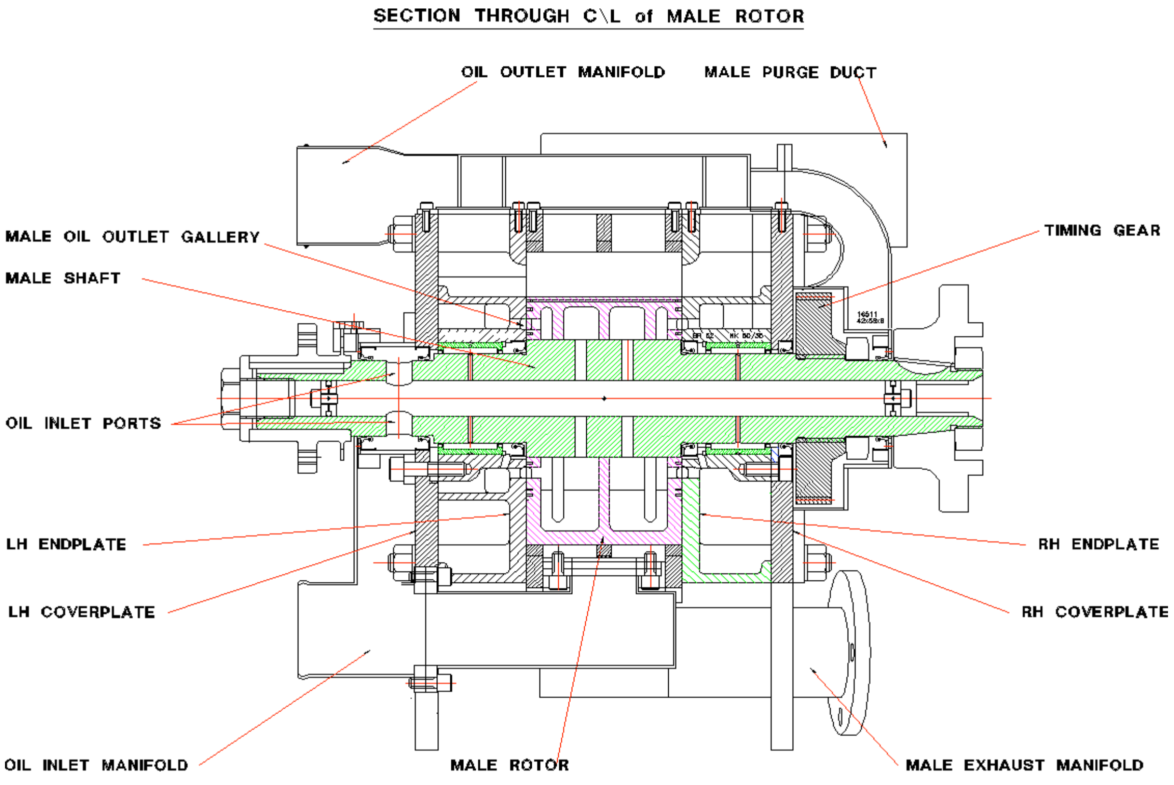
A new design layout was commenced to incorporate this proposal. The water pump and heat exchanger would be eliminated leaving just the oil pump with a larger heat exchanger. The oil inlet to the shafts and rotors would be one-way instead of the two-way water system. The bearings could be lubricated directly from the shafts. The male rotor cooling and lubrication oil would be introduced through the centre of the shaft. The rotor cooling outlet could be a series of slots in the end faces of the rotor with matching slots in the end plates. The rotor cooling oil would transfer through these slots into the end plates and combine with the housing cooling in a series of galleries. A partition would partially separate the rotor oil from the main housing flow. The female rotor cooling and lubrication oil would also be introduced through the centre of the shaft. The outlet would be through the far end of the shaft, passing through the timing gear housing and up into the cooling oil outlet manifold. This would mean one common oil outlet manifold.

Design layout

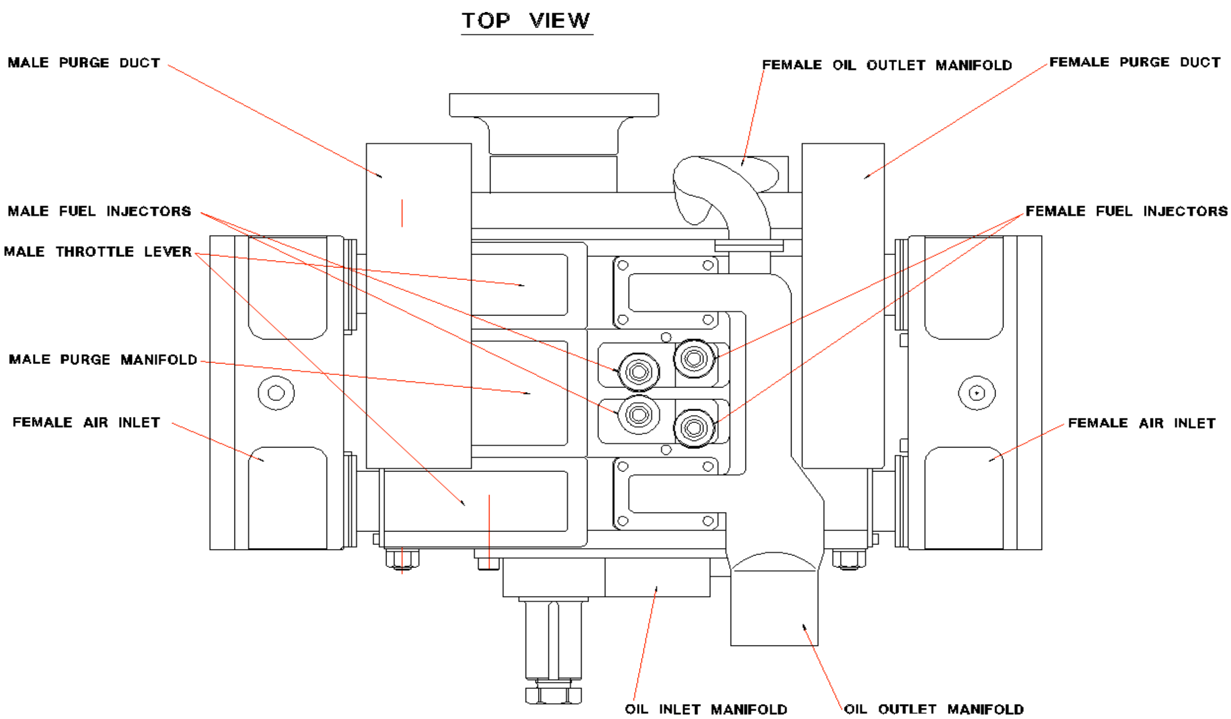
With these aims in mind, the design layout of the water-cooled 1000cc version, 6-1000.dwg, was 'saved as' 6-1000 OIL.dwg. This preserved the original drawing and allowed freedom to modify details at will. The rotor profiles and general layout were retained. The sandwich construction was also preserved. Almost all other aspects underwent a series of refinements and incremental modifications. A design layout of a 1000cc oil cooled version of the engine was commenced and various aspects of its current development may be viewed in Appendix **D-1** *6-1000 Oil Design Layoit.dwg,* **D-2** *6-1000 Oil 1.dwg,* **D-3** *6-1000 oil 2.dwg.*

The following four diagrams illustrate the Design of the prototype engine.
For more detail refer Appendix **D-4** *6-1000 Sect Thru C/L.dwg***.**



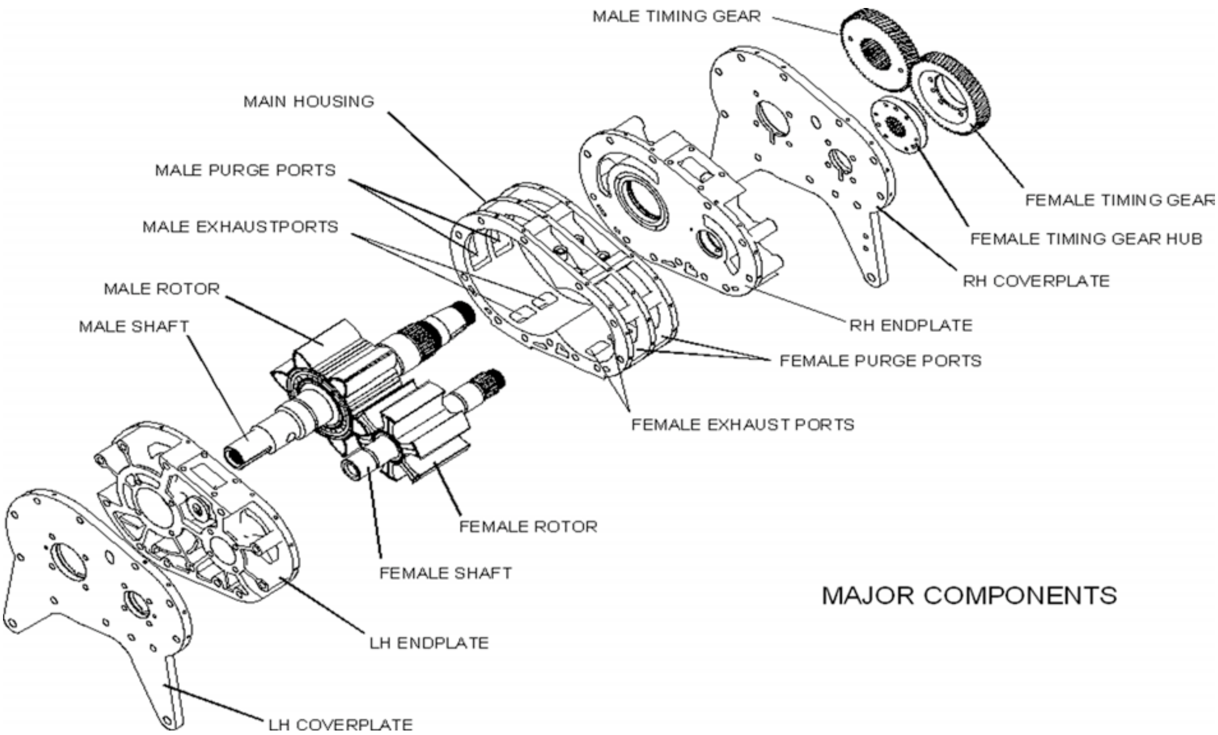


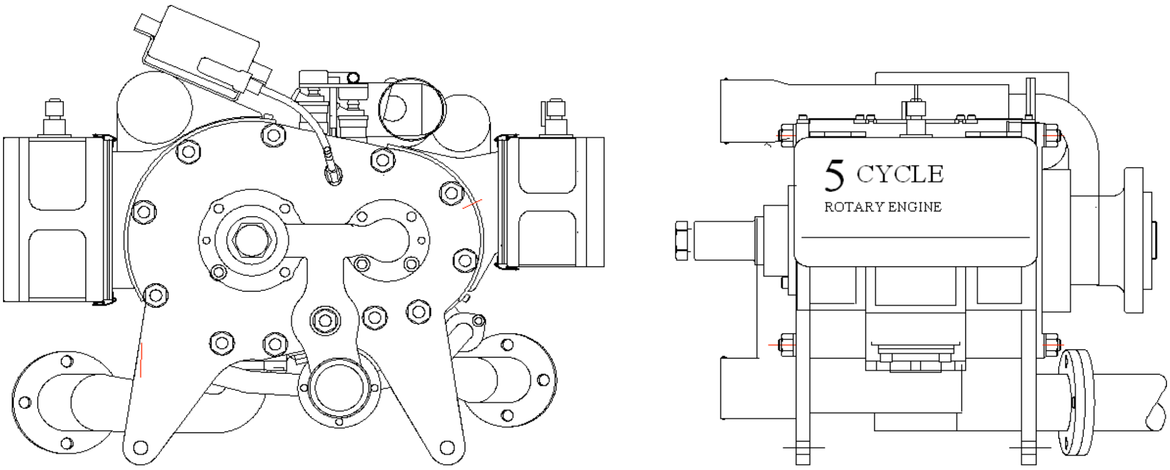
For more detail refer Appendix **D-4** *6-1000 Sect Thru C/L of Male Rotor.dwg***.**



For more detail refer Appendix **D-6** *6-1000 Top View.dwg***.**

The previous diagrams were intended to illustrate the importance of the detailed design layout in the development of the project. The following two diagrams are included to give an overall impression of the engine with an isometric exploded view of the major components and two orthographic external views.





External Views - 1000cc Oil-Cooled 5 Cycle Rotary Engine.

For more detail refer to Appendix **D-7** *6-1000 External Views.dwg***.**

Detail Design

I think it is important to reiterate, at this stage, that the drawings I am calling design layouts are the corner stone of the method I use to develop the design of a product from a concept through to the detailed design of each component necessary to produce a finished product.

A design layout is an accurate, orthographic drawing, containing as many views as is required to demonstrate the size, shape and relative position of all components. It is a drawing by the designer, for the designer. It is the venue for all the design decisions. The client may never even see it. Dimensions are not necessary if the layout is done using a CAD programme as CAD remembers everything it does with almost ridiculous accuracy. Notes and annotation are only necessary as memory joggers. It may start as a reasonably simple layout but normally develops quite rapidly in complexity, as each iteration of the detail being sought, is determined.

The design layout rapidly becomes the key document in the project as details of each component are extracted or derived from it. As the details of each part are resoled, they should be documented back into the design layout. This further establishes the design layout as the master record of the design. This is the case with this project and is exemplified, in this instance, in the detail design of the following components which were extracted from the Design Layout described in the previous section "Design Layout".

Main housing

The main housing was designed to be fabricated from bright mild steel components welded together to form the complete housing. This would then be machined and the inside surface case hardened with a final fine grind. As the housing is the central element, changes to the pieces surrounding it affected it directly. For this reason, it was in a constant state of flux. The design of the housing only solidified when most other parts were deemed complete.

Endplates

The endplates were originally designed to be cast from simple patterns with a straightforward 2^{o} per side draft, but as the design matured, it became obvious that this process was inhibiting the design. I finally redesigned the end plates to be produced by investment casting off steriolithographic master wax models from 3D CAD solid models. This method allows undercuts and wall thickness down to 3mm. These features were utilised to good effect. The final design has benefited greatly from the redesign.

Shafts

The male shaft was simplified by oil cooling and the use of longer, single-row, 50mm diameter, needle roller bearings on both journals. Oil cooling also simplified the oil inlet holes and improved the shaft to rotor oil transfer. The female shaft was redesigned to accept longer needle roller bearings. The timing gear mounting method was changed from a taper fit to involute splines. Involute splines have a gear tooth like shape. I have always wanted to design a part with involute splines, but had never had the opportunity. The normal practice is to use straight cut splines. The proposed manufacturer assured me that this was possible, as his father had bought a hob, which would be right for this job, thirty years ago and it had never been used. This was a satisfying indulgence on both our parts.

Timing Gears

The timing gears were designed with an 18^{o} helical lead angle. A pair of helical gears are much quieter than spur gears. The more important reason for specifying helical gears was to introduce a small amount of radial adjustment of the rotors to eliminate rotor-clash. The female gear has two components: a hub mounted on the involute splines, with a ring gear doweled and screwed to it. The gears are adjusted linearly with respect to each other by the addition of shims between the hub and ring gear. As the gears are helical, the linear alignment imparts a very small radial adjustment. This system has been used successfully to adjust rotor clash in roots type superchargers for a very long time.

The amount of radial excursion of the rotors is dependent on the degree of backlash in the gears and the linear movement of the shafts due to end thrust. The end thrust will be taken between the rotor end faces and the endplates. The anticipated end clearance is 0.1mm. The variation of rotor orientation caused by backlash in the gears and end thrust variation is absorbed by the spring-loaded tip seals in the female rotor.

Bearings

The bearings chosen for the male shaft are 50 mm diameter x 35mm long single row needle roller bearings at both ends. These have a nominal dynamic rating of 4400 kg. More than adequate for the task. The nominal rev. limit is 8000 rpm, but I have provided a radial clearance close to the maximum, 25 microns. This should allow excursions into the 10,000rpm plus range for short periods of time. The female shaft is fitted with 32mm diameter x 30mm long single row needle roller bearings at each end. These have a dynamic rating of 2950 kg and a nominal rev limit of 12,000 rpm. All four bearings run directly on the shafts without inner races. It is the current intention not to rev the prototype beyond 6500 rpm, if even that is indeed possible.

Lubrication and Cooling of the Bearings

The bearings are lubricated through holes in the shafts. The shafts have oil feed grooves around the running face. Three of the bearings are lubricated and cooled by fresh cooler oil. The bearing at the timing gear end of the female shaft is fed with the hot oil exhausted from the rotor. This is not ideal and will be one of the limiting factors with the engine, but was done in the interest of simplicity.

Spark plugs

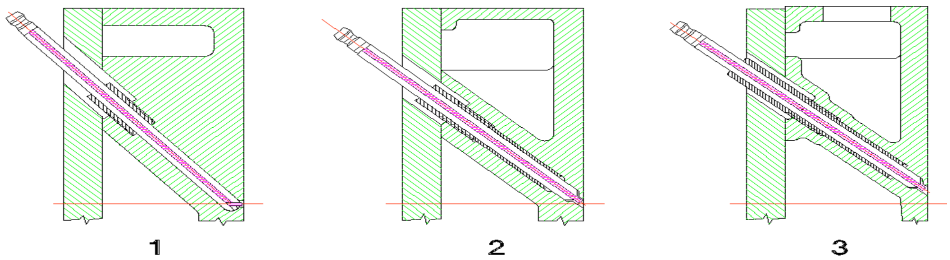
The spark plugs are designed specifically for this engine. There is a spark plug at each end of the combustion chamber. They fire simultaneously at the appropriate time. The combustion chamber is close to the centre of the engine. The earlier version of the engine (1357.dwg) was designed to be fitted with conventional spark plugs, but it was very awkward to position the plugs that far down, even with extra long reach plugs, and the resulting combustion space was too large. The 8mm diameter surface discharge plugs used in F1 engines may be the ultimate answer.

The spark plugs designed for the 28cc engine worked very well, so the starting point for the design of spark plugs to suit this engine was to simply to extend the length of these (Fig. 1). The electrode configuration in this design was difficult to construct. The spherical end required diamond grinding and the small hole for the electrode tip needed to be diamond drilled. The eccentric electrode made orientation awkward on insertion.

Fig. 2 shows a conical end on the alumina tube with a straight electrode. This is more straightforward to manufacture and solved the orientation problem. There is an added support tube with a separate clamp screw.

Fig.3 shows the final version with a combined strengthening tube and clamp screw extended, to allow easier access and to lend more support to the alumina tube.

The following diagram shows three iterations of the design of the spark plug. It also gives an indication of the transition stages of the endplate.



This is a practical example of design iteration.

Air Induction

The air is introduced through an air cleaner with a throttle mounted on a plenum chamber. Four ducts connect the plenum chamber to the four inlet galleries in the endplates. There is a male and female inlet gallery in each endplate leading to the inlet ports. The inlet ports form part of the fifth cycle. The fifth cycle may leave a small residue of burnt gas in the chambers. This should not be a problem as some manufacturers deliberately reintroduce, up to 11% of burnt gas to lower the combustion temperature from 3300^{o}F to about 3000 ^{o}F, as one method to the reduce NO_x emissions. It can reduce the NO_x content up to 60%.

The fuel is introduced by fuel injection early in the compression stage. There are two fuel injectors in the male chamber and two in the female. The two male injectors are set lean. The two female injectors are set rich and are spaced wider apart to impart their charge in the region of the spark plugs. The smaller rich charge is far more readily ignited than the larger lean charge and acts as a detonator for the lean mixture. This provides a form of stratified charge.

I expect the exhaust of the prototype to contain a higher hydrocarbon (HC) content for several reasons. Fuel injecting this late before ignition will not allow much time for evaporation so a portion of the fuel will still be in atomised droplet form. There will also be an amount of ‘wetting out’ on the walls and in the corners of the combustion chamber. The combustion chamber has sharp corners, which causes ‘shading’ and consequently a degree of incomplete combustion. There is lubricating oil content in the fuel, which will also result in additional hydrocarbon and solids in the exhaust. The accrued result could eventually be roughly equivalent to the emissions of the later Mazda rotary engines.

Cooling

The amount of cooling necessary is dependent on the amount of fuel burnt. This in turn is a factor of the thermal efficiency of the engine and the horsepower produced. The current heat value for 'normal' fuel is 44 Mega-Jules per kilogram. The expected fuel usage is 0.23kg of fuel per kW of power delivered per hour. It is anticipated that the prototype engine will deliver about 70 kW of power at 3500 RPM. This would indicate a fuel usage of 0.268 litres per minute, which equals a total heat input of 196.5 kW per minute. In a normal reciprocating engine, 5% of this would be unburnt fuel, 30% is discharged in the exhaust gasses, 30% is absorbed is absorbed by the combustion chamber and pistons and the remainder is useful power output. The 30% absorbed would correspond to 64.8 kW per minute. This is the heat, which needs to be contended with by the cooling system. The data on which these estimates are based was obtained from lecture notes, Vehicle Power Systems by Joel Hiltner at RMIT Bundoora Campus for the ME 487 Auto 1000 course.

The combustion chamber, valves, cylinder walls and piston crown of a comparable reciprocating engine has a combined area of 143,760mm^2, while the prototype 5 Cycle engine has an equivalent heat absorption area of 104,421mm^2. The prototype engine has 27% less thermal absorption area than its reciprocating counterpart. This will result in an increase in thermal efficiency. This means that the 30% figure for absorption could be reduced to about 22%, which gives the cooling system 47.5 kW per minute to contend with. The difference is a gain in thermal efficiency. This is all speculation based on data obtained from RMIT Automotive Engineering at Bundoora. It will be extremely interesting to compare the normal data with the actual test results.

The use of a Davies, Craig electric pump, with a maximum delivery rate of 1.2 liters per second, with an electronic speed controller will automatically vary the flow rate of the cooling oil to maintain the outlet temperature at about 100^{o}C (212^{o}F). A Ford aluminium radiator fitted with a thermally controlled fan will be used as the heat exchanger. This radiator is twice the size of that needed for a water cooled engine.

The cooling is introduced to the hot areas in the housing, first: the exhaust ports and the combustion area. The hot oil is then distributed to some of the cooler areas, but not all. It was not feasible to distribute the hot oil to all the cool areas in the prototype.

Since combustion takes place six times per revolution, heat absorption by the housing and the exhaust ports is almost continuous. The rotors cycle through: cold air induction to the heat generated by compression, combustion and expansion. The rotors obtain a small respite from the heat during the induction cycle, where they are additionally cooled during the purge cycle by the centrifugal induction of cool air.

The housing has no respite. For this reason, most of the cooling is directed to the housing. It does not matter how hot the housing gets, if the temperature is even over the whole expanse. Unfortunately, the prototype design does not include this rationalisation. The bridges in the exhaust ports should be cooled, however, in this design they are not. The result of uneven heat distribution and overly hot exhaust bridges will reduce running time and will result in poor seal life. The next version will contain solutions to both these problems.

Sealing

Piston rings are the main sealing elements in a reciprocating engine. They seal because they are fitted into a groove in the piston and are lightly sprung outwards against the bore. As pressure is applied to the top of the ring, it is forced downwards against the lower surface of the ring groove in the piston. This allows the pressure to insinuate itself inwards across the top of the ring and gain access to the annular gap between the bottom of the ring groove and the inside surface of the ring. This means that the pressure is equal on the inside of the ring and the outside bearing against to bore. This would allow leakage except that the small outwards spring pressure on the ring creates a correspondingly small outwards imbalance in the pressure, causing the ring to seal against the bore. As long as this imbalance is maintained, a seal will be affected, no matter how high the applied pressure. The action and shape of the components of rotary engines demand that the sealing elements be straight instead of circular. The same principle applies regardless of the shape, and merely means that the outward bias be supplied by small springs under each sealing element.

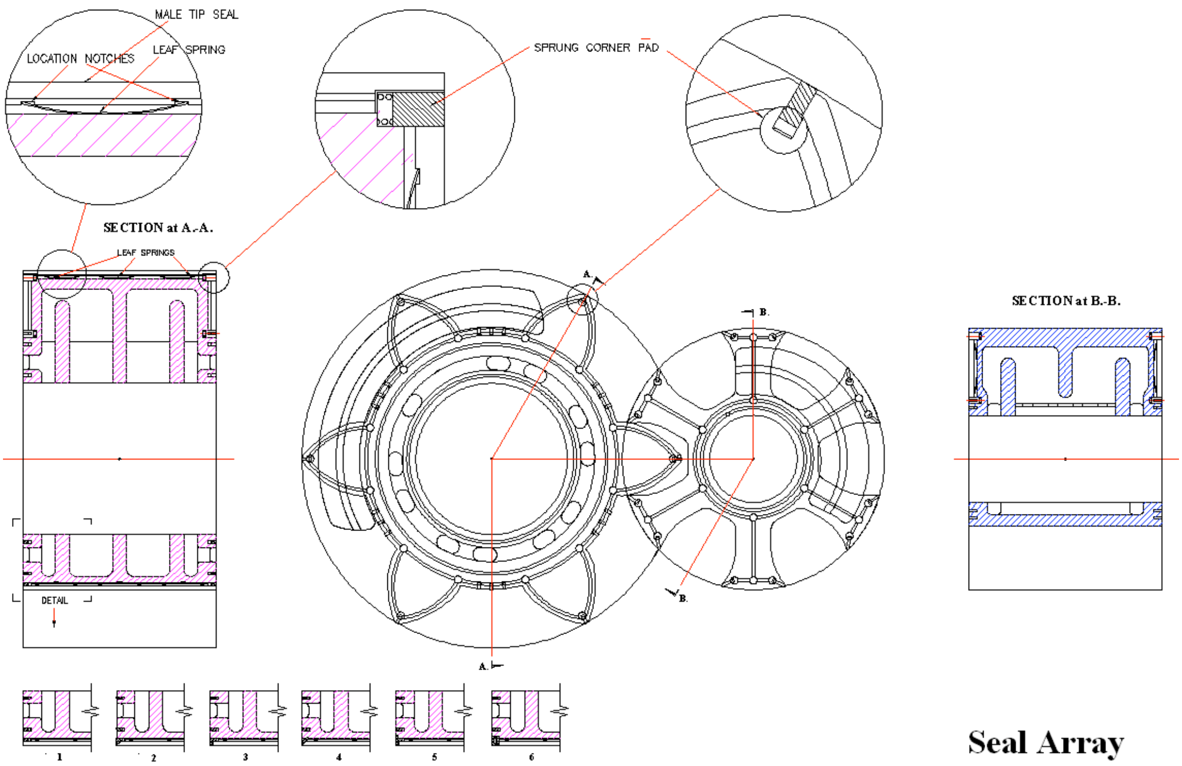
Sealing has been the ‘Achilles Heal’ of all rotary machines throughout history. The NSU-Wankel rotary engine embodies many successful solutions to the sealing problem. I have adopted and adapted many of these solutions. However, because this engine consists of two relatively complex gear-like rotors meshing intimately and needing to be sealed as they interact, several new problems have been introduced: maintaining the sealing integrity between the individual chambers formed by the ‘teeth’; sealing the tips of the male and female teeth against the main housing; sealing the outside diameter of the female rotor as it engages the root diameter of the male rotor. Sealing the rotors and the endplates is a very similar problem to those solved in the NSU-Wankel engine. Close-tolerance or proximity sealing, as used in rotary screw compressors, is not an option as most factors such as heat flow and speed are constantly changing. Sprung sealing elements also allow wider machining tolerances.

The sealing in this engine consists of four major types: tip seals; male rotor root diameter seals; end-face seals and corner pad seals. All the elements are individually sprung. There are 224 sealing elements in this design version of the engine.

Seal Array

The following diagram shows the general arrangement of the seals.

Refer to Appendix **D-9** *6 Seal Array.dwg.*



Seal Array

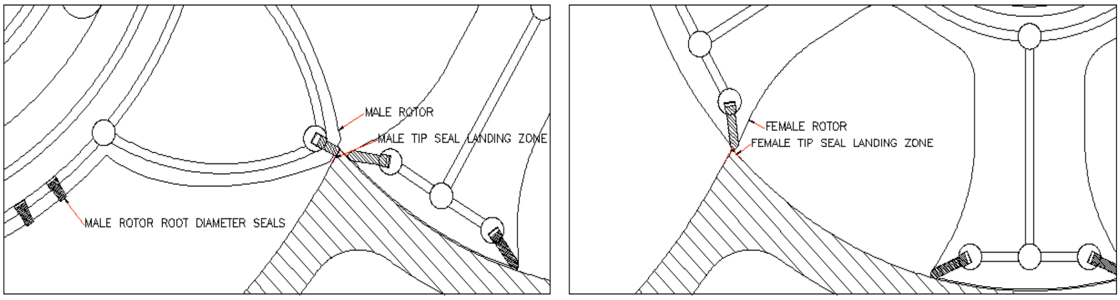
The diagram also shows the present solution to the sealing between the female tip and the root diameter of the male. A series of ideas, numbered 1 to 6 are shown. All six are flawed and will leak. The simplest to implement is No 1 and it will work as well as any of the other five. The totally satisfactory solution has not presented itself to me so far. The search will continue until it does.

The chase for a solution to the sealing problem illustrates another example of design iteration.

Landing Zones

This engine has ‘flying seals. The housing has a binocular shape. The tip seals, on both the male and female rotors, seal against the main housing for most of each revolution. However, there is a gap in the housing, during which the seals do not contact anything. They pass across the gap and are centrifugally cast into the void. It is necessary to limit the travel of this outward movement. The travel is limited to 0.15mm by introducing a small ‘tee’ shaped detail to the cross-section of the tip seals. The seal slots in the rotors have a corresponding 'tee' shape, sized to limit the seal movement with space for the seal springs. These flying seals need to land again, after they cross the gap. The landing zone is softened by a curved area in the profile of the housing. The housing is case hardened to 60 Rockwell C, and the tip seals are wirecut from steel hardened to 45 Rockwell C and tempered to induce toughness. The wirecutting process has the attribute of being able to cut the seal profiles from a previously heat-treated steel block with minimal distortion. This will enable the tip seals to withstand a reasonable battering. An equivalent battering could be the action of the cam followers in a reciprocating engine.

The following diagrams show the male and female landing zones. The male rotor root diameter seals can also be seen in the left hand diagram.



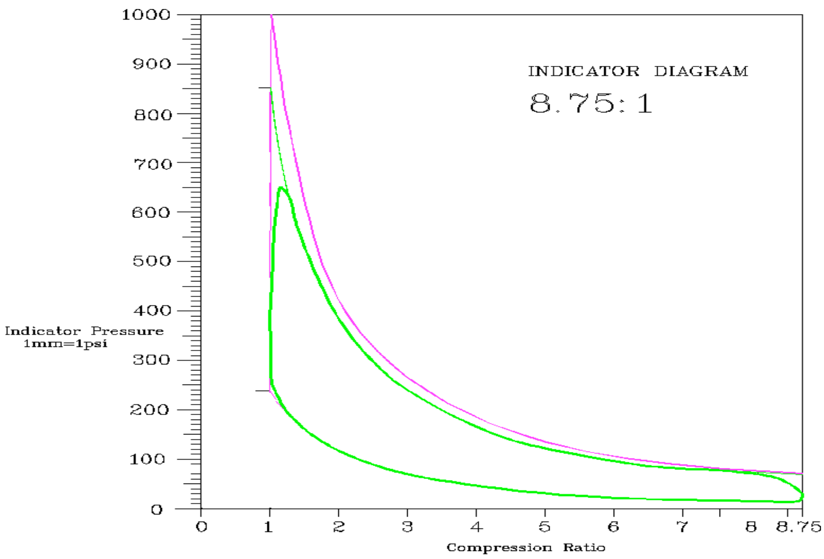
Even with the tip seals landing as softly as possible, I would expect the engine to experience seal flutter or bounce. This will have a tendency to cause surface corrugation in the main housing. Choice of materials and their treatment has been the eventual answer to similar problems in the Mazda rotary engine and should provide a satisfactory solution in this instance.

Gas will leak backwards from the chamber undergoing compression into the one following. In rotary screw compressors, this is gratuitously called 'slippage'. The leakage will be about 3cc out of 166cc at 1000 RPM, and will reduce in proportion to an increase in RPM. This will tend to lower the nominal compression ratio slightly, but more gas will leak backwards into the compressing chamber from the combusting chamber. This will raise the effective compression ratio again and more than compensate for the backwards loss even though it is with partially burnt gas. The combusting chamber will also loose gas forward into the chamber undergoing expansion. This will lower the pressure in the combusting chamber and increase the pressure in the forward expanding chamber. This provides an advantage as the forward expanding chamber has a better mechanical advantage than the combusting chamber.

Both compression and expansion are each taking place in two chambers concurrently for half the cycles. Consequentially the gas has to leak past two sets of chamber seals, with a lower pressure differential in each, before it is lost.

Evaluation

Having designed the engine in some detail, it was now necessary to ascertain whether it was worth proceeding further. The evaluation followed a similar approach to that adopted for the Lissajoux engine. (Refer to pages 46, 47 and 48). Once again a comparison was made with the same four-cylinder 2000cc reciprocating engine, except that this time it was compared with the No. 6, 1000cc Oil Cooled, 5 Cycle proposed prototype engine. Once again the same parameters were used for both engines. The torque output of both engines was calculated at various incremental points during a full cycle. The pressure in the chamber, at the progressive degrees of shaft rotation, starting at Top Dead Centre (TDC), was determined from the Indicator Diagram. Refer to Appendix **D-10** *8.75:1 Indicator Diagram.dwg.* The Indicator Diagram represents the chamber pressure in a typical engine with a compression ratio of 8.75:1. This was used in both cases. This Indicator Diagram does represent the cylinder pressures in a reciprocating engine.

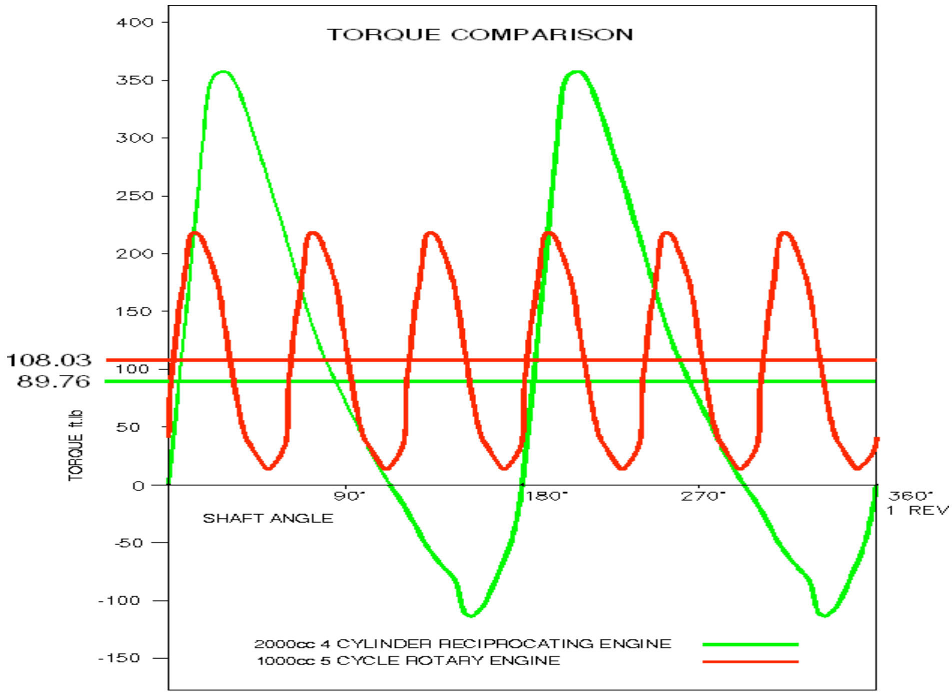


8.75:1 Indicator Diagram.dwg

The Indicator Diagram will not be true for the 5 Cycle Rotary engine, as the heat loss due to conduction and radiation to the chamber walls will be significantly less in the rotary engine. The rotary engine will also run hotter for being oil cooled. Both these factors will change the graph, and I will greatly appreciate obtaining more accurate information. However, in the interest of a direct comparison, the same Indicator Diagram was used for both.

The Torque of the Reciprocating Engine

The torque of the Reciprocating Engine is discussed on page 47, and was used again for this comparison. The vector diagrams for the reciprocating engine are depicted again in Appendix **D-11** *6-1000-Recip Comp.dwg.*



The torque of the 5 Cycle 1000cc Oil-Cooled Engine

The torque output of this engine was calculated by first determining the effective area on which the pressure reacts. Then by multiplying the effective area by the chamber pressure and by the average distance this effective area is from the centre of the shaft. The female rotor shades areas of the male rotor from the pressure while they are engaged. Consequently, the effective area is constantly changing. The full area of the male tooth is exposed to the pressure when the rotors disengage. The male tooth is fully exposed to the pressure for 60^o of rotation.

The effective area of the male tooth, the chamber volume and the moment to the shaft centre were determined by accurately drawing diagrams of the rotors, at the various rotation angles, using AutoCAD. 2D was adequate to obtain a very accurate result in this instance, as the profiles are linear along the central axes.

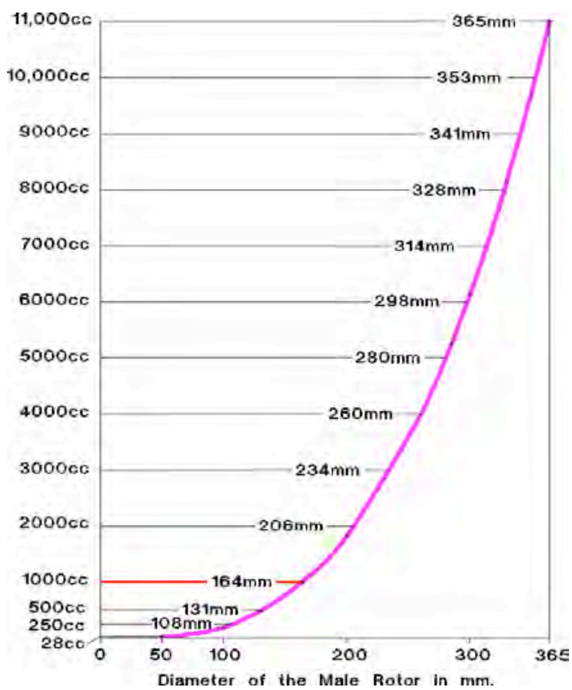
A more detailed drawing of the comparison method is depicted in
Appendix **D-11** *6-1000-Recip Comp.dwg.*

Advantages

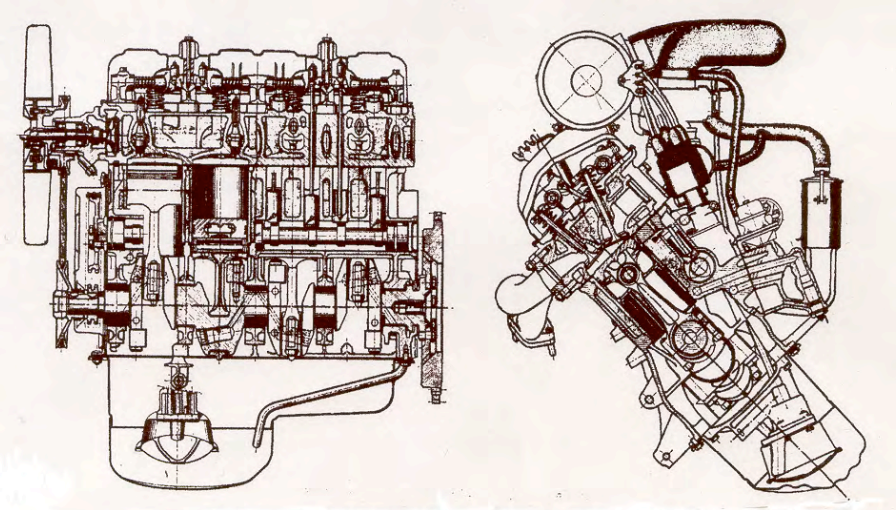
The **power/weight ratio** is exceptional. The actual components of the 1000cc prototype weigh 38kg. The materials used in the prototype are all steel or cast iron. The use of light weight materials like aluminium or magnesium alloys would reduce this weight dramatically. It is even possible to use titanium shafts if an application for extremely light weight is justified. This would result in the basic engine weighing about 25kg. The average 2000cc reciprocating engine weighs about 120kg.

The **power/size ratio** is also exceptional. Dimensions of the prototype are 300x300x300 millimetres, including an overly large air inlet system. These dimensions will be able to be reduced in subsequent versions. The size advantage is even greater as the capacity of the engine increases. The male rotor of the 1000cc (2000cc equivalent) version is 164mm diameter. To double the capacity to 2000ccc (4000cc equivalent), a male rotor diameter of 206mm is needed. An increase of just 42mm diameter. Doubling the male rotor diameter to 328mm results in a capacity of 8000cc (16,000cc equivalent).

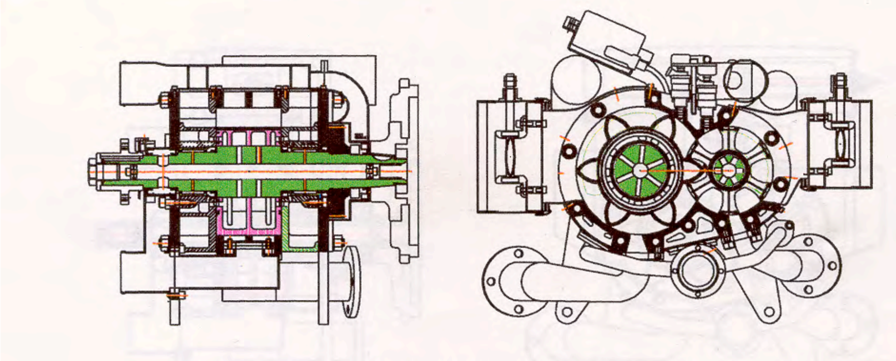
The following graph gives engine capacity relative to the male rotor diameter.



The drawings below show the relative sizes of the 2000cc reciprocating engine compared with the 1000cc 5 Cycle Rotary engine. The drawings of both engines are drawn at the same scale. The fuel usage and power output of both engines are similar. The drawing also depicts the relative complexity of the two types of engine.



Peugeot 504 2000cc Reciprocating Engine



Prototype 5 Cycle 1000cc Rotary Engine

Fuel economy should be a feature with further development. The comparison diagram (page 80) indicates that the 1000cc 5 Cycle Rotary would produce more power, per unit of fuel, than the compared 2000cc reciprocating engine.

The results of the torque comparison exercise shows the 1000cc 5 Cycle Rotary engine to have 146.4 newton-meters (108 ft.lb) average torque while the 2000cc reciprocating engine averaged 121.6 newton-meters (90 ft.lb) torque. This constitutes a nominal improvement of 20%. This is the direct result of the improved mechanical geometry of the 5 Cycle Rotary.
In addition to this improved mechanical effectiveness, a gain in thermal efficiency is expected as the prototype engine has 27% less thermal absorption area than its reciprocating

counterpart. The 5 Cycle Rotary also gains the considerable amount of energy consumed by the reciprocating action. As the 5 Cycle Rotary is port timed, a further major gain is the torque needed to drive camshaft and valve train.

The prototype 5 Cycle engine has relatively huge air inlet ducts and massive inlet ports so the volumetric efficiency is expected to be exceptionally favourable. The centrifugal action of fifth cycle saves the energy used by a reciprocating engine to generate the low pressure needed during the inlet stroke to draw in the fresh charge.

Extremely Smooth running with minimum vibration constitutes a major feature of this engine. The 'feel' of an engine is a vital factor.

Fuel Versatility is another advantage as the fuel is introduced into the chamber after it has closed, with a full quotient of air, and early in the compression phase. Thus means that the fuel volume is additional to the air. In the case of gas this is about 10% of the charge to be stoichiometrically correct. With normal manifold gas injection the fuel displaces about 10% the air, thus reducing the overall charge capacity by this amount. This would apply to any of the gaseous fuels such as propane, methane and hydrogen.

Reduced audible mechanical noise will be emitted by the exclusion of the whole valve train and the far lower number of moving and interacting parts.

Exhaust backpressure does not affect the power output. This would allow a very quiet exhaust system to be fitted. These attributes should allow the design of a very smooth running, quiet engine. It will also mean that the backpressure caused by a turbocharger will not influence the output of the engine. The design of a turbocharger may well benefit from a higher available pressure.

A very **small component count** would reduce production cost considerably. Material usage is dramatically reduced. The energy used to produce the engine should also be very much less than that used to produce an existing engine.

Disadvantages

As discussed earlier, **sealing** constitutes the greatest disadvantage in all rotary engines. This prototype engine is no exception. The side seals are experimental and will be the subject of intense development. There is a leakage path between the male side, or end, seals and the female tip seal. This will denigrate the performance and this problem will need to be solved in the next version.

The **flying seals** are intrinsic to this design and are a disadvantage. The prototype will demonstrate the magnitude of the problem they constitute.

Uneven heat distribution will distort the endplates. An endeavour has been made in this design to distribute the hot oil to the cool areas, in an attempt to offset this problem. However, fabricating the main housing limited the options and disparate heat zones prevail. This will also be improved in the next version.

Summary Evaluation

This engine promises to be exceptional in that it offers very smooth running with smoother torque output and potentially quiet running coupled with a very large weight reduction and with a greatly reduced size for a given power output. All this plus an indicated significant improvement in fuel economy. The power/weight and power/size ratio benefits are exaggerated as the size of the engine increases. I am sure that the disadvantages mentioned above will be solved with development.

The proposed design appears to be extremely promising. Certainly enough to engender an enthusiastic attack on the detail design and making phase. It is potentially a quantum leap forward in engine design.

Making

The processes involved in Designing and Making are obviously different, but they are interactive. The sense of satisfaction obtained from a potentially successful design is terrific, but it is always tempered by the anticipation of ‘will it be a successful product?’ Making a prototype of the design is a pedantic exercise and the satisfaction is obtained from producing the parts depicted by the design. The performance of the parts reflects back onto the design. Hence making instils an intense anticipation for the designer.

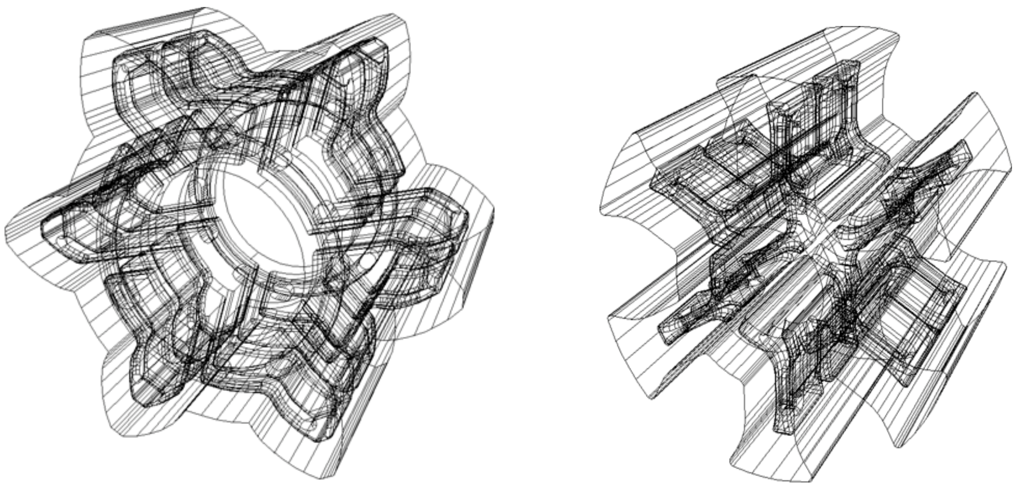
Male and Female Rotors

The male and female rotors have quite complex internal coring for cooling. The most appropriate method of manufacture was investment casting directly from steriolithographic wax models.

The details of the male and female rotors were taken directly from the 2D CAD design layout, a 1.0mm machining allowance was added and used to develop 3D CAD solid models of the male and female rotor. These drawings may be viewed in Appendix **D-12** *6 Male Rotor Wax.dwg.* and **D-13** *6 Female Rotor Wax.dwg***.** The machining detail of the Male and Female Rotors are viewable in Appendix **D-14** 6 *Rotors.dwg*.

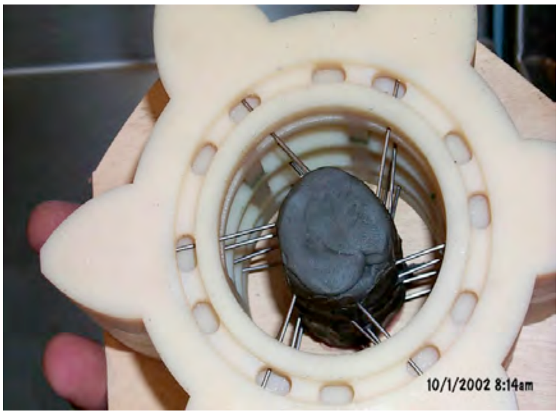
Male Rotor 3D CAD Model

Female Rotor 3D CAD Model

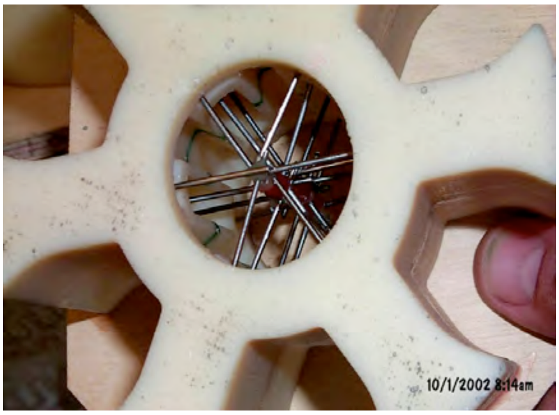


These models were converted to steriolithography files. The files were emailed to Queensland Manufacturing Institute. From these files, QMI produced wax master models with a shrinkage factor added. The waxes were then prepared for the application of investment.

Male Rotor Wax Master Model



Female Rotor Wax Master Model



The wires are to support the extremities of the investment in the cores of the casting. The investments were then fired, which evaporates the wax masters, and used to cast the rotors in SG600 cast iron.

The cast iron rotors were machined by Lovitt Technologies. The end faces were ground and the central bores were ground to be an interference fit to the shafts. It was proposed that the male and female profiles were to be 'stitch' milled in a 4 axis NC mill. The NC milling profiles were taken directly from the original 2D CAD design layout, and transferred to the milling operation as '.igs' extension files. They decided to wire-cut the profiles instead.

The tip seal grooves were milled using a 1.20mm wide slitting cutter. A jig was constructed to position both the male and female rotors in the milling machine. Refer to Appendix **D-15** *6 Tip Seal Groove Jig.dwg*.

The slitting process proved disastrous. The slitting cutter was mounted in a quill shaft which did not adequately support it. The first slot in the male rotor was cut cleanly but as the cutter lost sharpness, the blade was allowed to flex. Consequently the subsequent grooves drifted and diverted from straight. This damage to the male rotor had to be repaired. It required welding. Welding the cast iron rotor involved a special technique where the rotor temperature was raised to 250^{o}C in a furnace then TIG welded using very soft filler rod. Heat treatment was then required to stress relieve the casting. I then reshaped the rotor profile, by hand, to a template. The quill shaft was heavily reinforced and the slots were recut successfully. The same Tip Seal Groove Jig was used to end mill the holes for the small piston-like seals at the ends of the circular and curved end-face seal grooves.

Both the male and female tip seals have a ‘tee’ configuration to limit the degree of centrifugal excursion. The corresponding ‘tee’ needed to be machined at the bottom of the previously mentioned troublesome slots. I made a hand shaper to cut the ‘tees’ but was not able to exert sufficient pressure to the cutter. The final solution was to have Hardman Brothers wire-cut the ‘tees’ in both the male and female rotors using the CAD profile developed in the design layout. The technique worked extremely well except that an extra slot was inadvertently produced on the face of a male tooth. A repeat of the repair process except that in order to weld the rotor this time, two clamp pieces had to be wire-cut by Hardman Brothers to prevent the seal slot opening due to shrinkage induced by the welding process. A dummy Tip Seal needed to be wire-cut to fit the already ’teed’ slot to prevent the slot closing due to clamp pressure during welding. Unfortunately the weld penetrated a little too deep and welded the dummy Tip Seal to the rotor slot for a short distance. I was able to extract it but the sides of the slot were slightly damaged. The solution to this was to ask Hardman Brothers to wire-cut the ‘tee’ slot a little wider. This meant making a special Tip Seal to fit the oversized slot. Refer to Appendix **D-16** *6 ‘Tee’ Slot Profiles.dwg*.

Manufacturing the ‘Tee’ Tip Seals presented a problem as they needed to be hard, accurate and straight. Heat-treating of thin, long and finely ground parts would distort them. The answer was to wire-cut the ‘tee’ profiles from a previously hardened block of K245 steel ground to 82.80mm long. The wire-cutting process is very accurate and does not mind if the material is hardened. A light lap to improve the surface finish and to ensure a good fit in the slots was all that was necessary to complete the ‘Tee’ Tip Seals. This process also enabled me to produce custom profiles for each slot including the oversized one. Hardman Brothers also produced a jig to wire-cut the spring location notches on the back edge of the ‘Tee’ Tip Seals. Refer to Appendix **D-17** *6 ‘Tee’ Tip Seals.dwg*.

I then turned the circular end-face sealing grooves in the male and female rotors. I designed and built two shaper machines as additions to the Tip Seal Groove Jig. Refer to Appendix **D-18** *6 Male Groove Machine.dwg* and refer to Appendix **D-19** *6 Female Groove Machine.dwg*.

These were used to cut the curved end-seal grooves at each side of the male rotor teeth and the straight end-seal grooves in the female rotor. The individual high tensile aluminium end-face seals and the small piston-like phosphor bronze seals were shaped and hand lapped to fit.

Each of the 224 sealing elements is spring loaded. Experimentation with the spring materials and shapes for the various spring types determined the strength of each one.

The male and female rotors were designed to be a shrink fit on their relative shafts. The degree of shrink fit was 0.025mm per 25mm diameter. Liquid nitrogen was used to cool the shafts while the rotors were heated. The rotors were accurately positioned on the shafts and left to temperature stabilize.

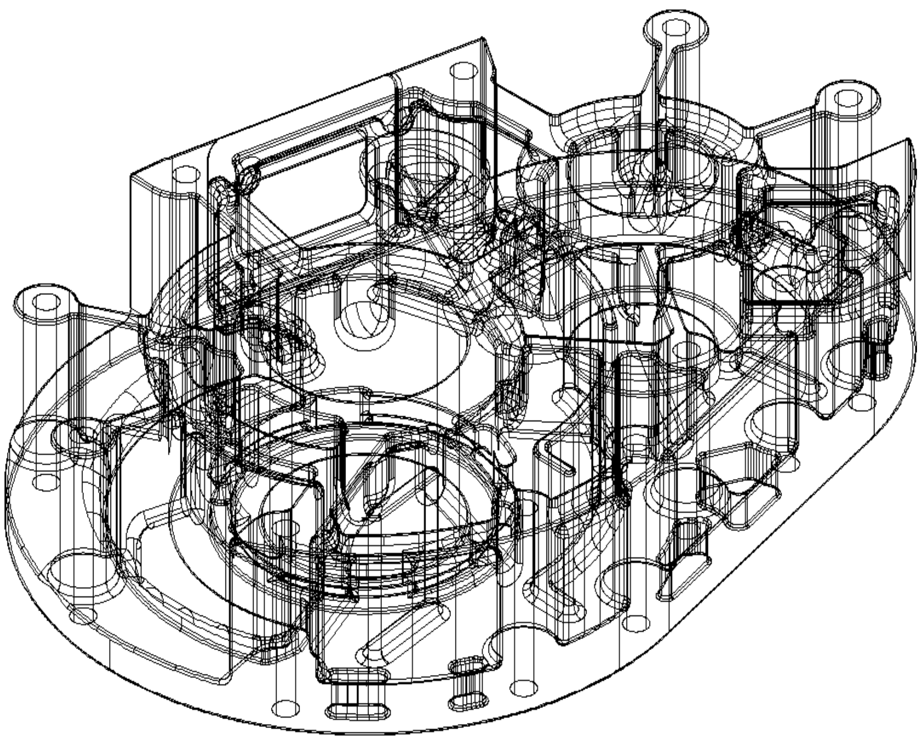
Main housing

The main housing was fabricated from bright mild steel. Two rings were rolled from 10mm thick plate. The diameters of the rings were appropriate to allow 2mm diameter machining allowance on the outside and 5mm diameter on the bores. The rings were machined on the outside then cut and scarf welded to form the binocular shape of the housing. Two profiles were laser cut from 10mm plate and one form 8mm. These were welded to the outside of the binocular shape to form three flanges. The two 10mm were welded on the outside edges and the 8mm at the centre. Sixteen blocks and ten tubular spacers were machined and inserted between the plates. The assembly was then welded to form the basis of the main housing. The excess weld material in the ports and around the posts was removed by hand grinding and filing. The bores were rough machined and the end surfaces were faced. The housing was then stress relieved and annealed. The bores and the end faces were machined again to within 0.25mm of the final size. The housing was milled in four places to admit the 16mm fuel injector mounting bosses. These were TIG welded to the housing and the inside surfaces were matched to the bores. The bores were case hardened to 60 Rockwell C and finally ground to a fine finish and close tolerance with special attention given to the centre distance. Matching the centre distance with the endplates is a vital aspect of this design. The tip seal landing zone ramps were stoned by hand. The tie bolt holes were drilled and five of these were reamed to accept specially ground tie bolts to act as dowels. The cooling oil apertures were added in the end flanges and three oil inlet manifold plates were welded in place to form the outer cladding of the cooling oil galleries.. The final act was to drill and tap the holes to accept mounting screws for the male and female primary exhausts, the four air inlet ducts and the two fifth cycle exhaust ducts. For the Main Housing machining detail refer Appendix **D-20** *6 Main Housing.dwg*.

This whole process was exceedingly time consuming and was done to save cost. The cost was saved but the effort was well and truly spent. Subsequent main housings will be cast, regardless of cost.

Endplates

The endplates were initially designed to be cast from simple pattens, but this restricted the design to the extent where I was forced to redesign the endplates to take advantage of the rapid prototyping method of production. The 2D CAD design layout was extrapolated to a 3D CAD solid model. Only one 3D CAD model was necessary for the endplates as they are the mirror image of each other. Mirror imaging can be done after the conversion from the steriolithography file to the file format used by the steriolithography machine to add the shrinkage factor and to insert the support flanges which enable undercuts. This process allows the design of the parts to closely approximate that of high quantity production techniques. Notably, it allowed the addition of wider sealing flanges on the outer edges of the ribs, a general wall thickness reduction and elimination of excess material around the spark plug. Detail of the Endplate is viewable in Appendix **D-21** *6 LH End.dwg.*



Endplate 3D CAD Solid Model

The Endplate Waxes with one layer of investment

The photographs show the wax masters being prepared in a 'tree'. The investment coating was built up to be approximately 10mm thick prior to firing.

The endplate castings were fine ground both sides and the spark plug details were milled and tapped. The inner face was the hard-chromed and fine ground for the final time. The inner face is hard-chrome to provide a suitable running surface with the end faces of the rotors to handle end-thrust and to give the end seals an appropriate bearing surface. The outer profile was matched to the main housing and the manifold mounting screw holes were drilled and tapped. Lovett Technologies carried out this machining and they also bored and ground the bearin holes. Unfortunately, they measured the centre distance of the timing gears at 113.67mm and bored the holes at this distance. The correct centre distance was 114.00mm. This was a disaster. Fortunately, Hardman Bros were able to remake the female timing gear with enough 'compensation' to adjust to the smaller centre distance. I was able to adjust the male and female rotor profiles to suit. The main housing had only just enough machining allowance to cope with the changed centre distance, For the machining detail of the Endplates refer to Appendix **D-22** *6 Endplates.dwg*.

Gears Shafts and nuts

The timing gears, the male and female shafts and the retention nuts were drawn in 2D orthographic drawings. These seven parts were manufactured by Hardman Bros. with great attention to detail. They were also able to remake the female timing gear as mentioned in the previous paragraph.

The shafts were made from EN3327 steel chosen for its toughness. They were rough machined, case hardened to 62 Rockwell C to a depth of 0.75mm, and fine ground to a tolerance of + or- 0.005mm. The fine tolerance is necessary when running the needle roller bearings directly on the shafts to gain the space normally taken by inner races. The case hardening was masked from the threads to leave them tough. The diameter available for the side seals on the female rotor is the constraining size factor of the whole design. The detail drawing used to manufacture the gears, shafts and nuts are viewable in Appendix **D-23** *6 Gears & Shafts Assembly.dwg* and the machining detail is viewable in Appendix **D-24** *6 Gears.dwg*, **D-25** *6 Male Shaft & Nuts.dwg* and **D-26** *6 Female Shaft & Nuts.dwg*.

Cover Plates

The Endplate oil cooling cavities are formed by two 12mm thick aluminium cover plates. There is one on each end and are extended downwards to form the engine mounts. The cover plates were milled to carry the shaft oil seals, and drilled and tapped to accept the oil inlet manifold, on the left hand end, and the timing gear housing on the output end. The cover plates are the bread of the sandwich construction. Detail of the Cover Plates is viewable in Appendix **D-27** *Cover Plates.dwg.*

Timing Gear Housing and Oil Inlet and Outlet Manifolds

The timing gear housing and the oil inlet and outlet manifolds are fabricated using 1.5mm and 2mm mild steel sheet, cut and formed then razed to 6mm thick laser cut mild steel plates. The oil inlet manifold is a little more complex. It has four inlet ports and is made up of four separate brazed assemblies screwed together to form the manifold. This was made necessary by the two extra inlet ports required to cool the two small cavities on the far sides of the exhaust ports. The next version will not need these two extra ports. Details of the Manifolds are viewable in Appendix **D-28** *6 Timing Gear Housing.dwg*, **D-29** *6 Oil Inlet Manifold.dwg* and **D-30** *6 Oil Outlet.dwg.*

Air Induction System

The air induction system is composed of an air filter and a throttle assembly mounted on a plenum chamber. Four ducts connect the plenum chamber to the inlet ports in the endplates. The plenum chamber is clamped to the four inlet ducts with four toggle action clips. This allows quick access to the fuel injectors.

The whole assembly is formed from 1mm mild steel sheet welded and brazed to 3mm thick mounting plates. Details of the parts are viewable in Appendix **D-31** *6 Air Inlet Manifolds.dwg.*

Exhaust Manifolds

The primary exhaust manifolds are constructed from 1.5mm stainless steel sheet formed and TIG welded to 8mm thick laser cut manifold plates. The almost continuous exhaust stream requires the extra temperature tolerance provided by stainless steel. Details of the parts are viewable in Appendix **D-32** *6 Exhaust Manifolds.dwg.*

Purge Manifolds

The male and female purge exhaust manifolds, associated with the fifth cycle, are constructed from 1mm mild steel sheet formed and brazed to 3mm manifold plates. Details of the parts are viewable in Appendix **D-33** *6 Purge Manifolds.dwg.*

Fuel Introduction System

The positioning of the fuel injectors provide a form of zoned induction or stratified charge (refer to page 82). The 'Hawk' fuel injection and engine management system was chosen for its additional flexibility as the two female fuel injectors need to be delayed relative to the males. The system is comprised of: the engine management computer, a high pressure electric pump with a pressure regulator, a fuel filter, air and coolant temperature monitors and a throttle vacuum sensor. The system is set up using an external PC. It allows the parameters to be manipulated 'on the fly' in real time.

The fuel is introduced through a specifically designed 'fuel-rail', which also clamps the four fuel injectors to the bosses fitted to the main housing. The bosses are necessary to allow the four fuel injectors to be as closely spaced as required.

Unfortunately, the current range of fuel injectors are solenoid operated and are duration controlled with a maximum duty cycle of 85%. The minimum open time is 1.5 milli-seconds. Each injector must open and close six times per revolution in this application. These parameters will allow the engine to run well to about 3,500 RPM and less well to about 5,000 RPM. This will be enough to demonstrate the potential of the project. The next version may well exceed 20,000 RPM. A continuously variable jet type injector would be a more suitable system for this engine. They do not exist yet. I have three separate design proposals, which might be developed in the near future: a voice coil device with cybernetic feedback, a stepper motor controlled pintle system and a pieazo tube cluster. All three would work. Which one would suit best is a question to be answered 'down the track'.

The pieazo tube cluster has a large degree of design elegance as it has the required frequency response time, and would eliminate the need for a high-pressure fuel feed pump in manifold injection systems. It would also deliver a finely atomized fuel spray mixed with air. A direct injection system would need the addition of a very-high-pressure fuel feed pump. Direct Injection, adjacent to the spark plugs, is the system I would dearly like to see ultimately utilized in this engine.

Ignition system

The 'Hawk" engine management computer also controls the automatic advance and retard facility for the ignition system. The CDI unit and the tachometer built for the Lissajoux engine, and installed on the 28cc No 6 engine, were used again with the dual discharge ignition coil. There is a spark plug located at each end of the combustion chamber and both fire simultaneously. The CDI is not necessary for operation but it lends the prototype a greater chance of success as it offers a much higher frequency discharge rate at a higher potential. One of its advantages is that it will excite twelve sparks at each operation in lieu of the normal single spark. Very high frequency indeed, but it will help ensure effective flame propagation.

Spark Plugs

The spark plugs have had to be specifically designed for this engine. The design is an iteration of the 28cc version. They were constructed from 6.1mm outside diameter x 1.8mm bore x 100mm long alumina ceramic tubing. A 1.6mm diameter steel electrode was sealed in position with alumina ceramic adhesive. A threaded external support tube was secured around the tube with the same adhesive. The operation of forming the conical ends on the alumina tubes was used as an excuse to dress my grinding wheel. The detail of the spark plug parts is viewable in Appendix **D-34** *6 Spark Plug.dwg.* A drawing of the profiles used to produce the laser cut pieces is also viewable in Appendix **D-35** *6 Laser Cutting Profiles.dwg.*

Test Bed

A ‘test rig’ was designed to mount the engine in preparation for the test series. This constitutes a tubular steel chassis, designed accept the engine, cooling system, engine management system and monitoring equipment. The sled was designed to marry the engine with a dynamometer. Detail of the Test Bed is viewable in Appendix **D-36** *6 Test Bed.dwg.*

Commercial Considerations

Patent

A patent search was conducted and seven US patents reveal similar thinking. None of them got to the stage where they thought that the fifth cycle was necessary. The main claims of this patent application will be concentrated on the ‘fifth cycle’ and the ‘seal array’.

A Lodgement of Application for a Provisional Patent was successfully conducted in Australia. The Patent office has allotted the number 2002952005 to the application. The ‘priority date’ date has been confirmed as 11^{fh} of October 2002 with the title of “A Rotary Engine”. The final lodgement in Australia, for a ‘Letters Patent’ would therefore due before the 11^{fh} of October 2003. International Patents would also need to be applied for by individual applications in each country before the priority date. The alternative is to take advantage of the ‘International Patent Application Pursuant to the ‘Patent Cooperative Treaty’ (PTC). This gives the advantage of delaying the date of application in each chosen country for thirty months from the original priority date instead of the usual twelve months. This equates to a rather valuable 18 months extension. There are approximately 105 currently participating countries. The cost for this privilege is about $10,000. The average cost of a patent in each country is approximately $5000 plus translation costs.

An International Application was filed on 10th October 2003. International Patents were required to be applied for before the publication date, which is 11th April 2004. Applications for International Patents were applied for in Australia, the USA, Japan and the European Block. I would preferred to include China and India, but application fees plus translation costs precluded this extra area of protection.

Costing

All manufacturers have their own preferred manufacturing processes and cost estimating systems. This means that arriving at an accurate cost estimate will depend on the manufacturers concerned and depends directly on the quantity and the degree of tooling involved. A reasonable cost appraisal could be estimated by direct comparison.

The design of a water cooled 5 Cycle rotary engine offers several considerable cost advantages over a comparable 2000cc reciprocating engine:

Low component count. The 5 Cycle rotary engine has **12 major** components plus the 'seal array'. A total of **72** parts. A comparable 2000cc, four-cylinder reciprocating engine has **48 major** components with a total of approximately **160** parts.

The mass of the 5 Cycle engine is about 20% of the comparable reciprocating engine. Consequently, raw material content would also be 20%. The 5 Cycle utilizes much the same types of materials as those used in the reciprocating engine.

Lower processing energy cost. The processes used to produce the 5 Cycle rotary engine are much the same as those used to manufacture the reciprocating engine. The difference is that there are a great deal less of them. Machining techniques are much the same. For quantity production, the male and female rotor profiles and the timing gears would be broached.

It is anticipated that the production cost of the major parts a 5 Cycle rotary engine would be about 30% of a comparable reciprocating engine.

Marketing

The attributes of the 5 Cycle engine recommend it to almost all applications. The exceptional power to weight and power to size ratios, The smooth and potentially very quiet running commend it particularly.

The **smaller capacity** range would be ideal for portable equipment, where weight and size are vital design requirements. This could include generators, air compressors, water pumps, and ancillary applications like refrigeration units in trucks and boats. It would be ideal in small motorcycles, small outboard motors, jet-skis, over-snow vehicles and micro-light aircraft.

The **slightly larger capacity** applications would benefit the design of smaller vehicles. The lighter weight and smaller size, for a given performance, would enhance the design options of larger motorcycles, outboard motors, small cars, stern drive units, jet boats, etc. The design of a hybrid car would benefit greatly from all of the attributes of this engine.

The **medium capacity** engine has the promise of offering car designers a new factor in the creative equation. It has been an ambition, in the back of my mind throughout this project, to eventually install a 5 Cycle engine in a car. Driving a car with a smooth quiet vibrationless engine would be a delight. However, I do not anticipate that this engine will make any great inroads into the automobile market, despite its potential. The modern reciprocating engine has developed to a stage where it would be very difficult to replace, and market resistance would be too large a factor. The creative designers could become enthusiastic but it would take a very brave and enlightened marketing manager to implement it. I can envisage its application in perhaps one or even two exotic cars. It would be beautiful as a competition engine as all its attributes could be fully developed and utilized there.

Larger capacity engine applications could benefit enormously, as the power/weight and power/size ratios become far more apparent as the engine capacity increases. *Refer* **P 68**. The design of propeller driven aircraft and would gain a great deal from the smaller profile and lesser weight of this engine. Trucks and ships would also gain valuable space and weight distribution.

An internal combustion engine with these attributes will be more likely to be appreciated as fossil fuel reserves diminish. Applications will always remain for a smaller and lighter engine, running on exotic fuels, where high relative performance is demanded. Propeller driven aircraft, smaller helicopters or high achievement vehicles would be examples where the demand will remain and high engine performance, relative to size and weight, will become even more crucial.

Business Strategy

The successful development of this new type of engine will demand huge resources and facilities to realise its full potential. For this reason, the attributes of the engine will need to be convincingly demonstrated before any serious interest could be evoked. The most vital aspect of a project of this ilk is publicity. The engine must be demonstrable but to continue, the undertaking must be brought to the attention of the world on a continuing basis. There are several development stages, which need to be implemented before serious development could be expected to be undertaken.

The prototype will be further tested and modified to a stage where it will indicate the potential of the design. Testing will also indicate a 'wish list' of improvements in future iterations of the design. This exercise will also enable the patent to be ratified and expanded. A detailed business plan will be prepared at this stage.

A Propriety Limited company will then be formed, using the current stage of development and the intellectual property as equity. Investment will be invited in order to raise capital to support the patent and to design and build a second version along with a subsequent development program.

The second version will incorporate a water-cooled housing. It will be designed and built using rapid prototyping methods, and will incorporate the improvements gleaned from the prototype test series. It will also be designed to embody lightweight materials like aluminium and magnesium alloys. The main housing and endplates will utilize more current hard surfacing techniques. This will reduce the weight by a further 30%. The intake and exhaust manifolds will also be reduced in size. This version should demonstrate the potential of the design more fully.

A third version would then be designed in several capacities. The sizes will depend on potential applications and the current level of interest. Several demonstration engines of the third version will need to be built for demonstration and trial.

At this stage, 'expressions of interest' will be called for. These may take many forms including direct investment in the company, 'joint ventures' or licensing agreements.

5

Conclusion

Chapter 1 and Appendix 1 outline a series of observations made of designers and designing over a great many years as a designer and design manager. In the particular instance of this project, I have followed the ideals and practices espoused. The ideas expressed form the basis of my actions and motivations as a designer. They have been applied in full to this project. This project is a practical application of these design methods. The design philosophy and implementation of the expounded methods would be viable when applied to many complex design projects.

The actual project is presented as a description of the design and manufacture of the Lissajoux engine followed by four case studies describing the progression of the design of the '5 Cycle' engine. The methods, materials and processes involved in the making of the actual parts of three engines have also been described.

Each of these designs comprise a step in the progression on the way to the research aim and consequently constitute 'research by design'. All five design exercises are examples of iterative design: step by step improvement of a design towards a goal. I have always practiced iterative design, however it has taken the introspective aspect of the PhD process for me to realise it.

With the aim of 'The Production of Power by Pure Rotary Means' this has been a design exercise of extreme proportions. The result has been well worth the effort. This project has culminated a life long ambition. The endeavour has resulted in an engine with attributes, which commend its application to those which demand high power, exceedingly lightweight, extremely small size, and is environmentally beneficial. This would indicate that if you stay with a design intention long enough, it would ultimately come to fruition.

The 'sense of satisfaction quotient', discussed in the 'Creativity' segment on page 12, has been consistently high throughout this endeavour. A firm conviction that this is indeed the case has influenced me to build a prototype of each of the progressive engine designs. Almost all the components of the prototype of the 1000cc oil-cooled 5 Cycle engine have been manufactured. It is my previously espoused belief that by far the best way to present a design is with a working prototype. In the case of a new type of engine, this is especially true. Unfortunately, at the time of presentation it still remains to finally assemble the engine and witness it running.

New knowledge has been added to the field of designing and the erudition of internal combustion engines as a direct result of this project having been undertaken and consummated. Not merely new knowledge, but a new and eminently practical device has come into being as a consequence of the pursuance of this particular set of goals. It also constitutes new knowledge in the sense of invention and innovation. The ‘Five Cycle’ engine is a new and exciting manifestation of the designated aim.

This project has consumed a large proportion of my later life and will, hopefully, contribute towards making the rest of it worthwhile. The underlying aim in all this was to benefit human endeavour in some way. This has happened and my original lifelong ‘rotary dream’ has been realised.

Appendix 1

Thoughts on Design and Technology

Creativity

The major aspect of designing is creativity: the ability of a designer to conjure new ideas or explore fresh avenues of an existing theme. This conjuring and exploration is facilitated by an ability to combine the use of a 3D-colour **imagination**, with a degree of sustained **concentration** and personal **commitment**. Perseverance is a trait, which is often needed to culminate a satisfying design. The degree of satisfaction derived from a design can often be a good indicator as to its probable success.

It is quite remarkable, in my experience, how often the solution to a design problem has been resolved in the toilet. After having immersed yourself in the details of a problem, following research and deep immersion in the problem, a satisfactory solution is often elusive. A visit to the toilet or a long shower relaxes the body and the mind and allows the imagination, or brain function, free reign. The result, in my case anyway, has quite often been an instant culmination of the various factors involved to become a satisfaction engendering solution of the problem.

This feeling of satisfaction with a design is the ultimate result. It has always been my goal, as a designer, to seek this sense of satisfaction in any particular design. It is possible to know, or at least sense, when the real solution to a problem has been attained. This chase for the sense of satisfaction is what drives most designers to do what they have to do. It is not equal for all designers or all projects. Some people are easily satisfied while others may chase a satisfactory solution for a lifetime, as has been the case with this project. Some projects yield a solution almost instantly while others remain insoluble and demand minimal compromise. Compromise dilutes the satisfaction quotient.

Imagination

In common with all other physical and mental abilities, imagination may be developed and the capacity expanded with practice. A good imagination is a necessary attribute of a designer to begin with, but it is possible to develop an increased imaginative competence.

As with the development of any other human endeavour, imagination takes a series of concerted efforts. It is possible to develop a simple concept into a complicated design in small increments or steps. In addition to the normal pictorial aspect, the imagination has an additional recording function. It might be likened to a video recorder. Once recorded, it does not go away. If you start an imaginative sequence with a basic concept and manipulate it until it becomes too difficult, stop there. It has been automatically recorded, and the next time you reconvene the memory, it becomes effortless to recall the image exactly as you left it. This leaves your imagination free to continue the development of the concept again until the degree of difficulty again becomes too great. Simply park it and come back to it later. It would seem that the process is a little like a computer with a thinking, or processing, facility with a separate inbuilt recording function.

While the imaginative manipulation facility takes a certain amount of effort, the recording function seems to be automatic. The next session is blessed with full recall of the images of the last session with the manipulative facility refreshed. Practice can extend the duration of a manipulative session and its suite of facilities.

Visual stimuli help. If an image becomes too complex to solve using imaginative visualization alone, it helps to sketch the last imagined image. It may be that a similar brain facility is used to create the sketched image as to record it. When you return to the imagination session, the sketched image is there, as though it had been recorded, and is just as pliable to manipulation as a purely imagined image.

Configuration, size, form, colour and texture are all manoeuvrable and once a static image has been established, articulation can be quite easily added.

Imagination can be developed to be a very powerful facility. As a solitary activity, it is very rewarding. As a group activity, it may become habitual.

Concentration

The ability to concentrate on a problem is also a vital necessity for a designer. This is also an ability that is expandable with practice. All of the ‘idea generation’ techniques like ‘brain storming’ or ‘word association’ or ‘morphological data’ are merely devices to engender concentration.

Group activity is a very useful and enjoyable way of stimulating concentration if the rule of ‘do not knock an idea’ is enforced. If you are not able to build on an expressed thought, no matter how ridiculous it appears, say nothing. A sense of humour sometimes helps. Brain storming is a powerful technique, and if repeated often enough by a particular group, may engender lifelong bonds. There is an example cited by Victor Papanek during a lecture series that I attended in the 70’s. A problem-solving group was formed in the USA composed of five people with multiple disciplines. The group was utilized by a number of firms over several years. The group was called in to help a boot manufacturing company to devise a ‘universal’ boot. After being closeted together for a week, they devised a knitted boot, which was not a satisfactory solution to this problem, but they did invent ‘panty hose’ and the machine to produce them. The company has since made a fortune from the sale of machinery for the manufacture of panty hose. They no longer produce boots. However, when one of the group left, the result was as devastating as a divorce or a death in the family.

There are many levels of concentration. In the interest of simplicity, I will only illustrate three. The first level might be conducting daily tasks like preparing breakfast and cleaning your teeth. The second would be the performance of a specific task like formulating a piece of writing or sketching a proposed idea. The third level is the most productive. This is where concentration is intense enough that ten minutes after you enter this state two hours have passed. This third state can be quite taxing and energy absorbing. For this reason, sufficient incentive is required to promote this state. In my own case, it can be induced by an intense curiosity as to the possibilities of a particular idea, or more normally, a client deadline.

Confidence in your own ability to solve a problem once you enter this third state can cause you to put it off until it is absolutely necessary. For this reason, a certain amount of self-induced commitment is necessary. Starting a session is at times difficult, especially if it is anticipated that it might be difficult. One ploy I use on myself is to say “I will only spend ten minutes this time, and then I will reward myself with a ‘jolly’”. Once started, it is difficult to stop until, at least partial satisfaction is gained. This sense of satisfaction is its own ‘jolly’ and I rarely need to reward myself.

Commitment

A personal commitment to t This commitment may be driven by practical necessity or by pure curiosity.

Some design solutions are arrived at almost instantly. For instance, a design direction may surface during the briefing discussion or during the first concentration session. Others might demand quite a deal of time and effort. The eagerness of a client to see tangible results puts a certain amount of pressure on the design process. Maintaining design application, in the face of difficulty, demands commitment. The goal of a successful design proposal is necessary.

Perseverance is also a valuable attribute in a designer. Not all design solutions give a full sense of satisfaction. It may satisfy the need for the moment, but if the ingredients are left to fester in there, a real solution may surface as things change in the future. This 'rotary engine' project contains an extreme example. The ingredients of one important aspect of the project had been at a 'subliminal fester' for thirty years before surfacing at the behest of a slightly different stimulus and a minor change of application.

Incentive

The previous statements of the value of design are all very well, but if the basic ingredient is missing, nothing will happen. What drives us? Why are we driven to do it? Most designers no not choose designing as a career because nothing else was offered at the time of choosing. It is very much more complex than that. Most people who eventually become designers are recognised early in childhood by parents or friends as having the skill to express themselves graphically. Praising children for demonstrating talents causes them to try even harder in order to garner further praise. Fostering graphic talent at school is gaining credence. As a result, the number of students applying for undergraduate design courses is rising. The current acceptance rate is well below 10%. Consequently, the talents are further filtered and concentrated. Finding yourself among a group like this tends to promote an aspiration to learn and having learned have a desire to apply the knowledge.

Designers also need to be imbued with a natural desire or need to improve things. A heightened awareness of the wrongness of an object, and possessing the means to correct it, quite often prompts a designer to act. Not always though. The observed transgression needs to be very bad or a personal affront, otherwise the designer is likely to do as I do. That is to consign the project to the 'gunna' bin. One of these days I am gunna do something about that! I have a very large personal 'gunna' bin.

The necessity to resolve a design project is prompted by a variety of needs. Financial reward is the most common incentive. The need to keep your family in the manner they to which have come to believe you could. And you may be prompted by the need to prove yourself as good as or better than your peers. Or you may be goaded by threats. There is usually a degree of each of these which drives us. It matters little what particular factor has motivated the designer to action, because, in the end it is the satisfaction of a job well done which will engender further design activity.

Most professional designers are forced to develop a ‘dry start’ technique. That is the ability to be introduced to a project that you would rather not tackle, and be able to take a particular aspect of it and say ‘yes I would like to do it’. Invariably, when introduced to the problem, it is almost impossible to let it go until it is solved to the satisfaction of all involved. This is the nature of most good designers.

It is quite rare for a designer to be presented with the opportunity to contribute their talents towards a project that is close to their own hearts. This project is certainly that and I have embraced the opportunity to the extent that I think my soul-case is a little larger.

Design Research

Design is such a vast subject that, in its pursuance you may need to follow your own area of interest in an effort to limit the scope of research to a practical level. Design research comes in two main flavours: research by study and research by design. Both are usually necessary during the pursuit of the satisfactory resolution of a design project.

Research by study includes: relative reference material, historic data, previous designs, both documentation and product examples, publications, periodicals, patent material and significant information from any source. It is normally a time consuming, patience absorbing, pedantic process, but generally produces rewarding results. Knowledge is its own reward. And in the quest for it, wether prompted by pure curiosity, a need to know, or by a client standing on your head, I have invariably been delighted by some aspects of what I have found.

Research by design is valid and is an extremely relevant form of research. It is quite often the design activity that induces true innovation. It is normally exemplified by the “what if” supposition. Given the design to this point, ‘what would happen if’ a particular parameter were to be changed or rephrased or were to be made less stringent or even deleted altogether. This is a favourite approach of mine, especially when confronted with a dogmatic or overly rigid client. All design activities should remain flexible, and when confronted with rigidity, it is my natural inclination to remove **all** pre-conceptions, conditions and constraints, and see what happens. I have found this approach to be the most rewarding of the design tools available. Not because it is the most effective method of research, but because it has resulted in the most personal satisfaction derived from a project.

Design research most often employs graphic methods, from rough thumbnail sketches through renderings to highly detailed CAD drawings. It is usually an incremental iterative process and has been utilized extensively and is demonstrated many times during the present project.

The Environmental Aspects of Design

The world is currently suffering from a people plague. There are far too many of us. The population increase and the rise in the standard of living have presented the environment with a disastrous scenario.

The potential for design to influence the environment is vast. Design for ‘whole of product life’ is an excellent aspiration, and the use of apposite materials and processes can greatly reduce the impact of a product on the environment. The current aim is to minimize the impact. However, even minimal is not enough. The real aim should be to have no influence or if possible to have a positive effect. We must stop the degradation. The design process offers a superb opportunity to actively help address the potentially cataclysmic eventuality.

There is a finite quantity of each element on earth. Some, like iron and sodium are abundant and some like the rare-earths used in electronic components are rare indeed. Most of the elements, especially the metals, exist in a dilute state and require to be concentrated in order to be useful as constituents of products being designed. The energy and materials utilised in this concentration process should not be wasted. The utilization of virgin materials is a luxury which is not sustainable. *The materials we have now are all we will ever have.*

An immense tonnage of vital material is currently disposed of by burial or incineration. The practice of recycling products and components is still in its infancy. The energy and materials used in the recycling process must be balanced against that required to garner virgin materials. The elements contained in the discarded materials remain on earth, unless they are sent into space. However, as the raw materials are progressively gathered, concentrated and subsequently discarded, they are inevitably dispersed. Eventually, over eons everything will be naturally recycled, but in the meanwhile, the resulting dispersal will make it increasingly difficult to re-harvest the materials humanity needs to continue its rape of our environment. This imposes a responsibility on designers of all disciplines: to utilise materials and processes judiciously and to design in order to facilitate retrieval of the basic content in any discarded object or material. Effective retrieval is one of the most important aspects design can contribute towards a solution to the problem. If we are not able to establish control of the utilisation of useful materials and effective re-dispersal of waste materials we will initiate the devolution of the human species and most other species with us.

Judicious use of processes is another area which is the responsibility of design. The processes involved in the manufacture, preparation and finishing of materials are also potentially disastrous. For example aluminium could be considered to be solid electricity and the acids used by the plating industry impose a heavy impost on the environment. The relative cost to the environment of a very large number of materials is available from most universities and it behoves all designers to make themselves familiar with the comparative figures. A web search for sites containing the words 'environmental effects of materials and processes' using Google reported 2,800,000 sites.

On Industrial Design

A general definition of Industrial Design could be 'The design of goods for use by people'. This includes everything, which may be built or manufactured. Convention dictates a few exclusions: Architecturally designed buildings; that portion of aircraft design, which is the province of Aeronautical Engineers and the Naval Architecture sector of ship building. This leaves a large area of potential activity and spans from 'one off' pieces to the design of products intended for high quantity production. The design of 'one off' or limited production products definitely has its place in today's society, but the main area of concentration of the Industrial Design contribution is the design of goods for 'mass production'.

As with all professions, Industrial Design is utilized where an economic gain could be expected from its use. The cost of introducing a new product to the market place is counted in millions of dollars, before the release of the product onto the market. Industrial Design is a significant factor in reducing the considerable risk involved in the introduction of a new product. About one in ten product designs could be considered successful.

Any new product needs to fill a market niche. It also needs to appeal to an identified target market. This 'appeal' is a vast subject. It encompasses the aesthetic appeal of a product, involving all five senses, plus a 'fit for purpose' factor. This 'fit for purpose' is also a vast subject. It includes evaluations like: how well does it work; what is its life expectancy; how energy efficient is it; how easy is repair; what portions of the product are recoverable when it is eventually discarded; what is the imposition on the environment during its manufacture and the time the product exists. These are a few of the many concerns of a dedicated Industrial Designer.

Another concern, after having produced the proposed design for a product, which incorporates these goals, is to ensure the design integrity during the period of its culmination. Product engineers and production engineers are experts in their field, and are charged with producing practical tooling and an efficient production technique. However, in their concentration on these goals, they need to be convinced that that extra degree of difficulty imposed by your design may be necessary. The opposite may also be the case. This may be where a change to the design eases their burden without determent to, or improves, the final product. It is vital for an industrial designer to have the technical knowledge to design a practical product in the first place and to appreciate the aims of the other disciplines. A collaborative approach is by far the best, where all the people involved work toward a solution to each problem, which satisfies all disciplines, while maintaining design integrity.

The Team

Industrial Design is a team activity. The team normally consists of representation from management, marketing, finance and engineering. **Management** has the task of approving the project and ensuring that it proceeds smoothly. **Marketing** must consult their crystal balls to predict and order the future success of the project. I confess that I have always thought the way marketing people walk with their knees thrust outward was a sign of arrogance, but I now realise that this is a merely a ploy to protect their very sensitive crystal balls. I remain convinced that **finance** is completely dedicated to putting the ‘kibosh’ on everything, no matter what. **Engineering** are sure enough of themselves that it does not matter anyway. Industrial Design must find its place among the team. It usually fits comfortably somewhere between marketing and engineering.

One of the most effective attributes of an industrial designer, apart from creativity, is communication. Some of my most rewarding moments have been as a result of participating in ‘planning’ meetings with various teams.

‘A picture is worth a thousand words’, and during these meetings I have had the opportunity to sketch my interpretations while the thousand words were being expounded. I will cite three examples.

The first was during a meeting in 1964 with Ogden Industries (Lockwood) where the future of a series of ‘door furniture’ was being discussed. I sketched like mad. The direct result of that meeting was a new range of ‘door furniture’, most of which is still on the market, and continues to do well after nearly 40 years.

The second was at Techtron (before it became Varian Techtron) where a group of us contemplated a very messy room full of scientific equipment. A series of sketches were generated representing the ideas expressed. The result of that session was a bench-mounted atomic absorption spectrophotometer. An analytical instrument that is capable of, quickly and easily, determining the calcium and potassium content of blood and the lead content in urine samples donated by miners, in parts per million. It is also used by the miming industry for on line monitoring and assay work. It was idle curiosity of the team, which exposed the unusually high mercury content in fish in Port Philip Bay to the newspapers at that time. The resulting instrument, the Techtron model AA7 won the scientific section of the Prince Philip Prize for Australian Design in 1968. The Prize, together with the press photographs are still in my third draw. That exercise became the basis of a whole new scientific industry based in Melbourne.

The third example is of a monthly product planning meeting at General Electric where the marketing people expounded their thousand words on the market opportunity for a low cost 'water boiler' to compete with the very low cost and ubiquitous ceramic jug of that era. Kettles were expensive at that time. I sketched solidly for two days. The sketch proposals met enthusiastic approval. I subsequently set up my own team for research and development. The result was the General Electric plastic kettle, one model of which won the Prince Philip Prize for Australian Design outright in 1978. That prize is still on my mantelpiece. The kettle was awarded the 'J Mark' in Japan in 1979 and is currently on display in the Powerhouse Museum. The product remained on the market until 1999. It attained a product life of 25 years. The normal design life of a product is about 3 or 4 years.

The reaction of the team is a very good indicator as to the prospective success of a design. In this instance, everyone was enthusiastic and we all knew that we were working on a good one. This enthusiasm transmits itself to the marketing and sales team and this almost guaranties a successful product. I got the impression that even finance was pleased, despite themselves.

Models

If 'a picture is worth a thousand words', a good model is worth a dozen pictures. The presentation of a model almost always elicits a comment from someone like "Oh, is that what you have been on about' or "It is smaller than I had imagined" or "The colour does not seem to be quite right". This, in the face of having been previously presented with, and had voiced their approval of, a dozen sketches and high quality coloured renderings. A photographic quality model offers the ability to see, feel, smell, taste and truly appraise the proposed design. It also gives the marketing manager the opportunity to twist a knob off the model after just having arranged a photographic session for later that day.

The ideal presentation is a **working** photographic quality model. It is an order of magnitude better than a solid photographic model. This is usually only possible after the engineering input is at a relatively mature stage. A 'breadboard' model would have been built. A 'breadboard' is a model with all the operating components assembled and working, but with no consideration given to positioning or the eventual shape of the object. It renders vital input to the final design layout, which should reflect an amalgamation of the data gleaned from the 'breadboard' and the previously proposed shaping of the solid model. A final working photographic quality model can then be built. During testing it invariably reveals aspects of the design, which are in turn incorporated into the design layout. This design loop may be repeated several times during a complex project, especially if there are new or unknown aspects involved.

Form and Function

Industrial design is considered to be the marriage of art and industry. A debate involving the age-old question of ‘does form follow function’ or visa-versa has a tendency to cause the participants to polarize their arguments. The true answer is that each design should reflect a maximum quotient of both. It depends largely on the project as to where the emphasis is placed. The project under discussion here, the rotary engine, is an example where it could be expected to contain a heavy bias towards the functionality end of the spectrum. This is true of course, however, if the principles of ‘good design’ are applied to each component, the overall effect will acquire an aesthetic appeal. For instance, castings are essentially ‘free form’ objects and lend themselves to being nicely shaped. The external components like the air inlet and exhaust systems also furnish an opportunity to apply ‘good design’. The stated aim of the project: ‘pure rotary motion’ also embodies a fundamental aesthetic contribution.

Good Design

Each well designed object should contain a full measure of technically founded functionality plus an aesthetic appeal. The major contributing factor towards aesthetic appeal is a sympathetic treatment of the **form** and **finish** of an object.

The **form** of an object is usually established by completing a preliminary design layout then conducting ‘form studies’. The preliminary design layout should be undertaken early in the design process. It is normally represented as a three view, orthographic drawing. This is done to gain an appreciation of the approximate size and shape of the object. It should incorporate all the known factors and data to that point. This ‘known factors and data’ is intended to include: the materials and processes proposed to produce each part, the size, shape and tentative position of all intended components. This forms a good basis for ‘form studies’, which are usually a series of rough models shaped from polystyrene or polyurethane foam.

It is almost impossible to accurately judge the size and shape of an object from an orthographic drawing. The most graphic example of this is a cylinder with a height equal to its diameter. In an orthographic drawing, this takes the form of a circle and a square with sides equal to the diameter of the circle. A model of this appears amazingly tall and slim. The same phenomenon happens when curves and radii are added to a block model. The proportions and apparent size may be altered drastically. For this reason, an accurate model is necessary when attempting to establish the final size and subtle shaping of an object. The model may then be transposed back into the design layout.

The final shaping of an object is an art. It could be taken to be analogous with sculpture. Pascal formulated geometry for the construction of curves, which he claimed, are the basic curves of nature. They do look pleasing, so he may be correct. This geometry is used in the aircraft and automotive industries to establish aerodynamic shapes around ‘hard points’. Hard points are the established, immovable, mechanical reference points around which, a shape is established. Pascal’s curves closely approximate parabolic shapes. If a radius is formed across the top surface an object and a smaller radius is applied at the edges, it appears to be kinked at the junction of the radii. This effect has been dubbed ‘pixie earring’. In order to cure this effect, the car industry talk of adding a ‘blend radius’ between the two. This is only half the answer. Parabolic shapes are far more pleasing. An example might be the shape of a half-worn tablet of soap or that of a well-sucked lolly. The rate of change of a nicely formed curve is an important factor in the final perception of an object. The use of a simple radius is crude and does not constitute ‘good design’.

The **finish** of an object has a profound effect on the way it is perceived. Finish, in this context, may be taken to mean texture, colour and applied graphics. A white object tends to appear larger than the same object with a black finish. A matte black object tends to loose the subtleties of form when compared with an identical object finished in gloss white. A high gloss finish tends to appear and feel harder than a satin finish. A high gloss finish also shows imperfections very nicely. Surface texture, like applied patterning, tends to hide blemishes. These are extreme examples, however the same effects may be observed, proportionally, with all the colours between black and white and the textures between matte and high gloss.
The graphics applied to an object may also have a dramatic effect on its apparent size and shape. They may even change the perceived function and value of a product. For example ‘go faster stripes’ on a car or a brand name on a piece of apparel. Many women know that black is slimming, vertical stripes tend to accentuate shape while polka dots disrupt the comprehension of form. Even small or subtle application of graphics can influence the perception of an object extensively.

Design Method

At the beginning of the design phase of a new project the outcome is usually unknown. It is exciting to visualise and sketch the first proposals. The more informed the proposals are the better, but until the designer makes that initial proposal, or series of proposals, nothing of practical use exists. This adds a sense of adventure to a new project. All aspects of a particular design are interrelated, and changing one aspect usually affects every other thing. If the design is considered to be fluid, there is a large degree of freedom imparted. The fluidity of a design gains viscosity as 'knowns' are set down.

Over the years I have developed a 'design method' which works for me. I would like to mention a few aspects which I have found useful. The particular design method outlined here applies to Industrial Design and to Product Design in particular.

It is an extremely helpful exercise to document a set of initial naïve thoughts before any serious research is undertaken. Normally several pages of thumbnail sketches will be enough to refresh the memory of these early thoughts when more deeply embroiled in the throes of the design process. I have found that it is quite often helpful to refer to these sketches.

The obvious starting point is to research areas such as: client product history, competitor product history, promotional material and trade magazines. A patent and design registration search is often justified and has been made easier and far more accessible by the internet.

The idea generation and exploration stage has been covered earlier and should produce enough material, usually in the form of thumbnail sketches and renderings to establish a design direction. It is now appropriate to produce a rough, three view, orthographic design layout in order to gain an impression of size relationship and proportion. This rough design layout is enough to proceed with form studies, which usually comprises a series of foam models. Foam models may vary in quality from wire-cut styrene foam to sanded, coated and painted fine grain urethane foam.

Enough is known now to produce reasonably realistic concept renderings. Usually three: one conservative approach representing a direct interpretation of the client brief, the second presenting your own approach incorporating any innovations and advancements, and the third a slightly "way out" version to highlight the fact that your preferred solution appears a little more conservative than it really is and consequently more easily accepted. It has been my experience that the initial presentation is likely to promote vigorous discussion and disparate opinions on almost all aspects of the design. If you do not get a strong reaction, go back and do it again. The normal result is a rather reluctant consensus. Enough, though, to divine a direction for the designs to be represented in the second set of rendered proposals. The second presentation is usually more concerned with the rationalisation of details. The third presentation is usually a formality, conducted in order to approve the design, to appropriate the finance and initiate the project. It always seems to take three presentations no matter what I do. If I anticipate the three phases and endeavour to proceed through all three in one session the result has been even greater confusion. It would seem that the people who make the decisions need to be led gently and progressively through the process. This has not always been the case. A very small number of clients have been receptive to the design stimulus and have grasped the opportunity to participate in a truly gratifying experience. The world would be a much better place if there were more of them.

Following approval, the project gathers legs. Now it is real. Immediately those areas of design conjecture proposed in order to make the project viable, need to be resolved realistically. The venue for the resolution of these design points is a more detailed design layout drawing.

A detailed design layout drawing is the crucial nub of the conversion of an idea to a realistic resolution of a project and is needed to realise the next phase of the project. Photographic models are required at this early stage to gain management and marketing approval and to allow marketing to plan advertising and 'point of sale' material. The design layout is also used to engineer a working breadboard model. The breadboard model is an assemblage of the working parts totally without aesthetic considerations. It is engineered to develop the working aspects of the product. Detail part drawings are also drawn at this stage to be used this early in the project by product engineering for tool quotes, purchasing department to arrange 'long lead items' and production engineering to design the production line and plan the facilities such as the needed plant and equipment.

The procedure that I am calling a 'design layout' is an accurate, 1:1 scale, three view, orthographic drawing showing everything superimposed, using solid lines and containing all known detail. This would include wall thickness, edge detail, ribs, flanges, fixings, curves, clearances between parts and anything which might influence the design in any way. It is you talking to yourself so there is no need to conform to the Australian Drafting Standards. There is no need for dimensions or notes except where you may want to remind yourself of a detail. The design matures and consolidates to a stage where the design layout is the master document and is the centre of reference for the project. For this reason, the design layout is required to be maintained with progressive updates.

In the not too far distance past, a design layout had to be drawn on glass-cloth using a 12h chisel shaped lead to maintain stability as paper can vary in size as much as 1% overnight due to the change in humidity. The advent of mylar film improved the designers lot a great deal in that it is stable and fine grain and it became possible to print an ‘acute’. An acute print is also on mylar film with the sensitized surface placed directly in contact with the pencilled side of the drawing. This reduced the parallax error engendered by the print machine and produced very accurate and stable prints able to be used directly by pattern-makers and tool-makers.

These days the use of Computer Aided Design (CAD) has transformed the engineering aspects of a project. A design layout produced using CAD should contain the same elements and aspirations expressed as being included in the ‘longhand’ method described above. The essence of design is change and a major advantage of CAD is the ease of incorporating change.

The method I advocate is to draw the initial layout in 2D with common reference points established in each view. The 2D profiles can then be expanded into 3D. The method expounded by the producers of CAD packages, is to design directly into 3D. This is fine if the project is simple, however if the project is more complex, change tends to abound. The more complex the change, the more difficult it is to keep track of reference points and consequently the easier it is for confusion to creep in. It is not usually the first set of changes that cause trouble but the fifth or sixth set may well be. If a secure set of references is maintained in the 2D base drawing, it is relatively straight forward to change the profiles and cross-sections and reconstruct the 3D elements and incorporate them. I have found the use of this style of design layout has been repeatedly beneficial in this project. I will draw attention to the many examples as they occur during the project.

Another major advantage of CAD is the ease of progression from 3D CAD models to working photographic models using current rapid prototyping methods. I have utilized many of these processes in this project and will highlight them as they emerge.

The industrial designer should remain vitally involved through the engineering phase because each of the disciplines involved has their own emphasis and usually want to change the design to suit their specific needs. The disciplines normally associated with the design are product or project engineering, production and manufacturing engineering With the best of intentions, they are eminently capable of ruining the design. The industrial designer should have the engineering knowledge to answer the challenges and work with each of the other disciplines to reach equitable solutions while maintaining the design integrity of the project.

The present project demonstrates an applied example of this design method except that the chosen project is biased toward the engineering side of the spectrum and I am my own client. Consequently some of the design stages have needed a slightly different treatment. However, the general design approach and method has been utilized and demonstrates that the principles espoused work very well when applied to a very complex project.

CAD in Design

When undertaking a design exercise of reasonable magnitude, a practical starting point is to manually sketch a rough preliminary design as close to scale as reasonably possible without ruining the spontaneity. The practice results in a rough design layout, but it is an excellent starting point for an initial 2D CAD design layout. The design layout can then be progressively modified as areas of concentration manifest themselves.

The iterative design process is a natural method of proceeding a project. The progressive design changes constitute the essence of iterative design. One of the many advantages of CAD is the ability to modify the current design easily and to record the incremental changes which accrue. This makes CAD an ideal tool of iterative design. If there is a doubt whether the proposed change will be an improvement, it only takes a moment to copy the whole or a part of the design layout to a new space in the same drawing. It is then possible to modify either copy with impunity. This adds a very effective degree of design freedom to the design process.

Another advantage of CAD is that it is extremely pedantic. However, this tends to be a disadvantage in the preliminary design stage. As the design progresses the iterations mature. It is an easy process to rationalize dimensions and tidy up the details of the design.

These days the trend in Industrial Design is to design directly in 3D CAD. It is my contention that to draw any proposed product directly to 3D CAD results in an artists' impression of the proposal. This is fine, if that is all that is required, and it can be an excellent starting point. It may also work well for simple projects. However, most projects are not simple, and progress through a series of modifications. Modification of 3D models requires established data points and datum lines. I remain convinced that the most convenient method of recording these data for reference is to start with a 2D design layout containing all the reference material needed for extrapolation into 3D. This allows profiles and data points to be readily accessible when modification becomes necessary.

Drawing directly to 3D CAD satisfies the art component of Industrial Design, but there is an additional stage necessary to inject the produceability factor. It is necessary to convert this artist's impression to a producible product. The first stage in this process is to rationalize the dimensions. My usual practice is to round the previously indiscrimate, or loose dimensions, to the nearest 0.5mm. The second step is to incorporate the use of available materials and processes. Pushing the boundaries is also a basic tenet of Industrial Design but this is normally tempered, in part, by practicality.

In this project, the various design layouts were drawn with these precepts in mind. They were all drawn, to a degree of accuracy, which allowed the details of each component to be extracted directly to a separate set of individual drawings. This is a relatively straightforward process, using 3D CAD, where the most casually placed line is recorded in the database, to an accuracy of sixteen decimal places of a millimetre.

It is also normal that a number of components be presented to the manufacturer as 2D orthographic drawings. It will take another generation before everyone is fully conversant with total 3D. There will always remain applications for 2D orthographic drawings.
My preferred method is to develop the 2D design layout and extract the individual aspects of each part and developed into 3D solid models and oriented relative to a common datum point. This results in an array of the pieces, which can then be copied to another datum. I have

found this the most convenient method for the reason that, although there is very rarely trouble encountered when joining the various pieces of a component, there is a great deal of trouble encountered when inserting the final filleting operation. Nearly all corners and edges need to be filleted to impart strength to the final part. If corners and edges are left sharp, internal and external stress will cause the part to fail. Inserting the fillets is usually tried initially on the final assembly.

Programmers for PC based CAD programs develop their algorithms to produce the result they think the end user might need. This result has rarely satisfied my needs on the first try with any part, which is in any way complex. There is a plethora of methods able to be utilised to circumvent these shortcomings. It usually involves reassembling the part from the individual pieces in a different order. If an array of these pieces is available, this is a straightforward process. If the part has been drawn straight to 3D CAD, redrawing is a very laborious process.

Invariably, in a new design, modifications will need to be made to the part. If an array of the individual pieces of the part is available with common data points, modification of these individual pieces may be affected reasonably easily. If a more profound change is required, the original 2D profiles, with data points, are available from the 2D design layout.

I have successfully used this method of development for all the components in this project, which require 3D CAD solid modelling.

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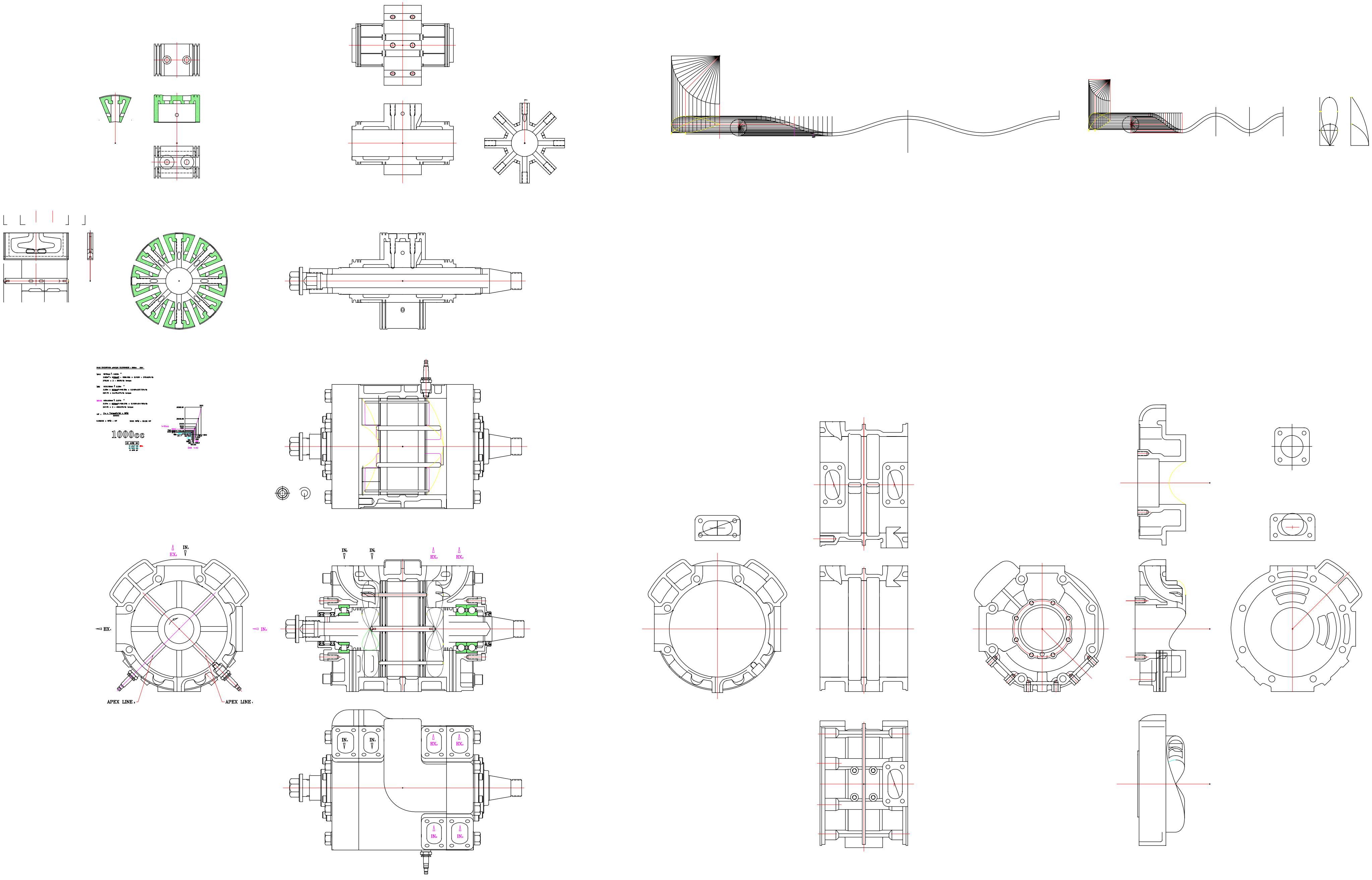

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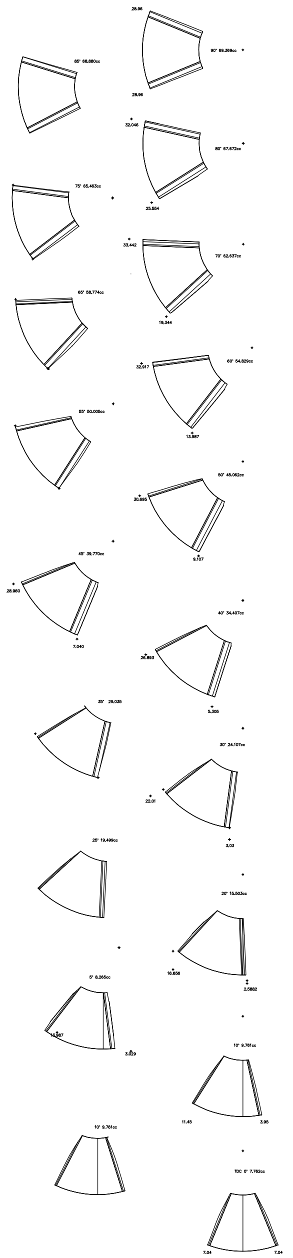

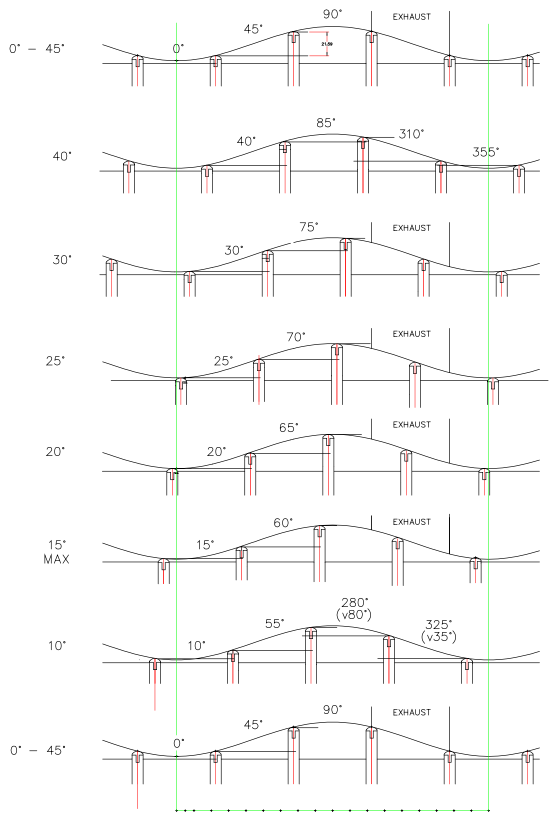

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40° – 85°
130° – 170°
65.146ft.lb

30° – 75°
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20° – 65°
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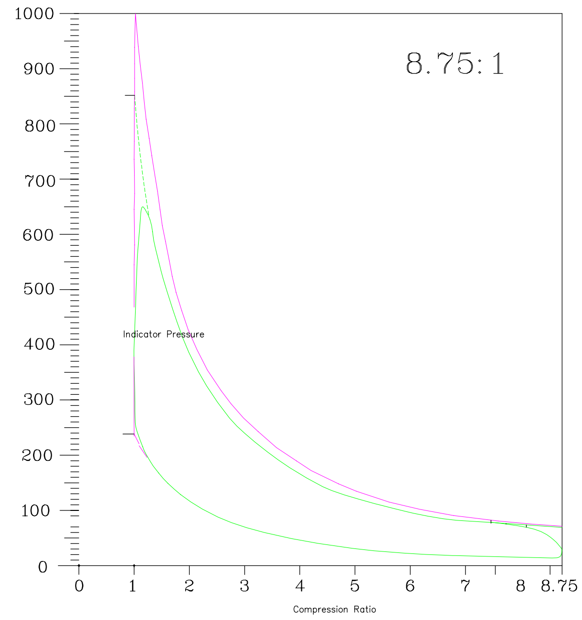

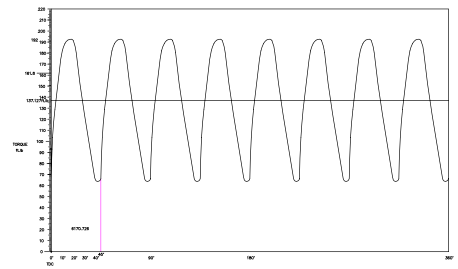

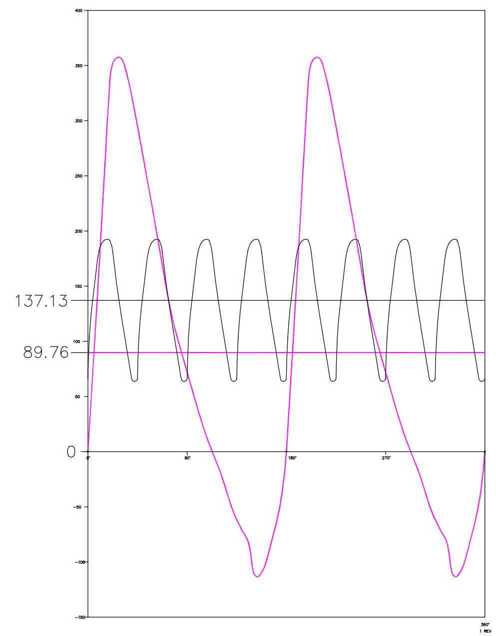

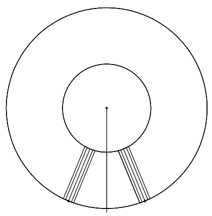

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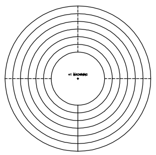
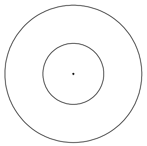
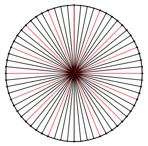
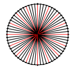
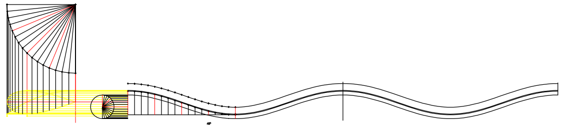
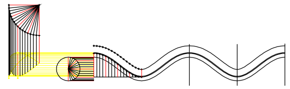
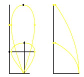
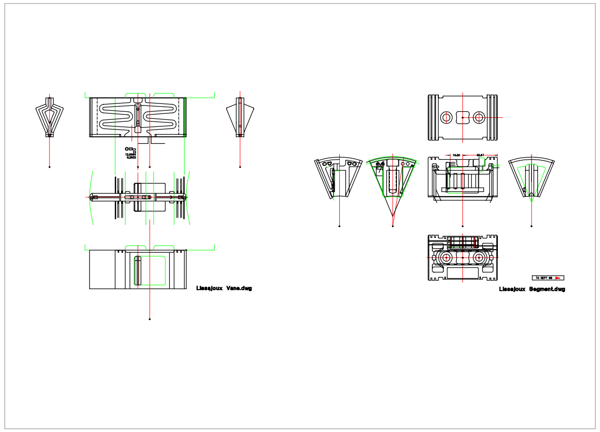
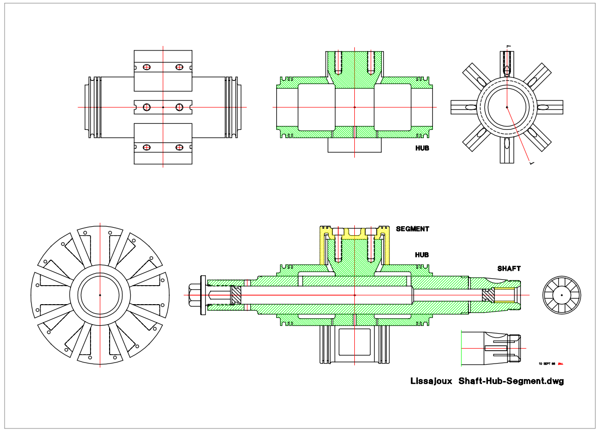
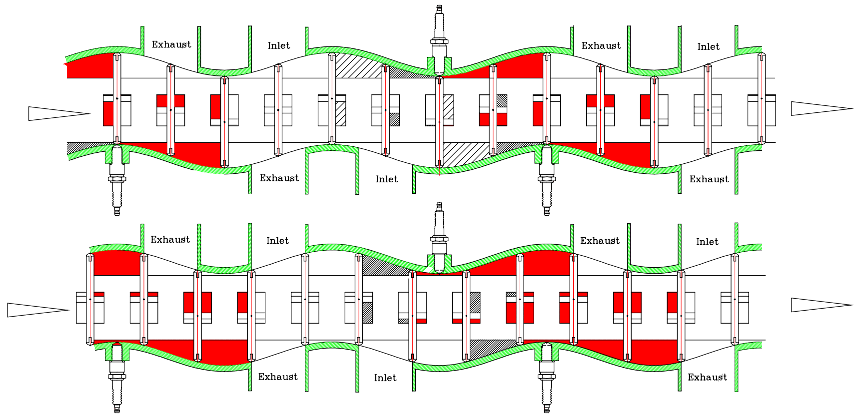
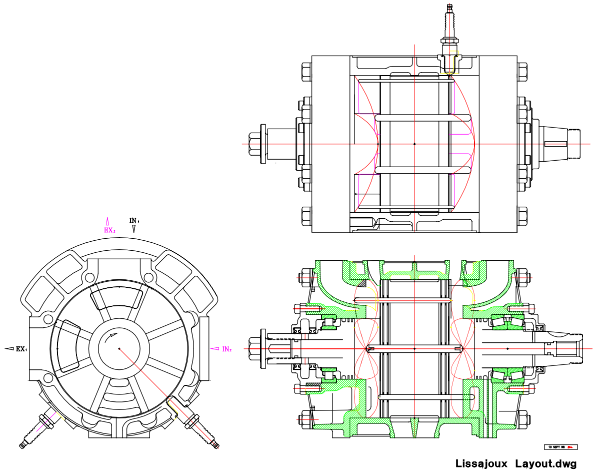
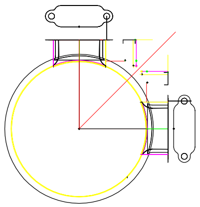
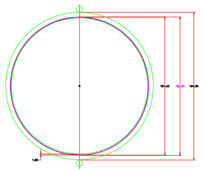








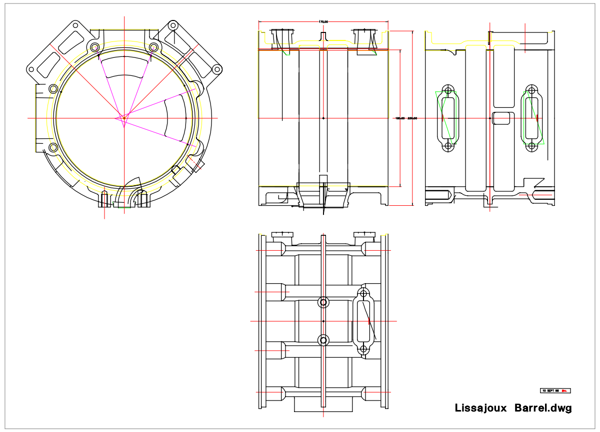


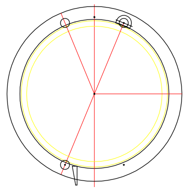


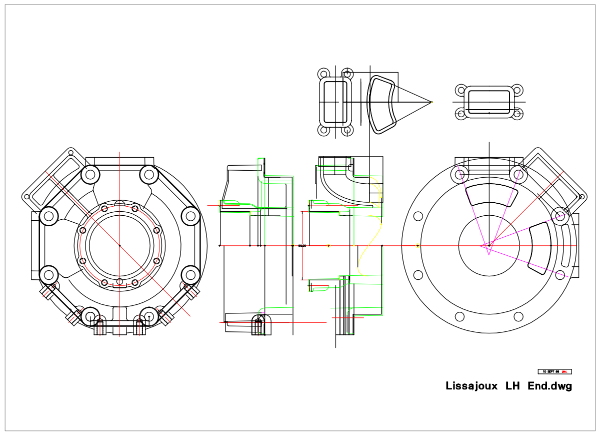


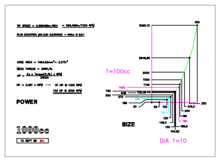




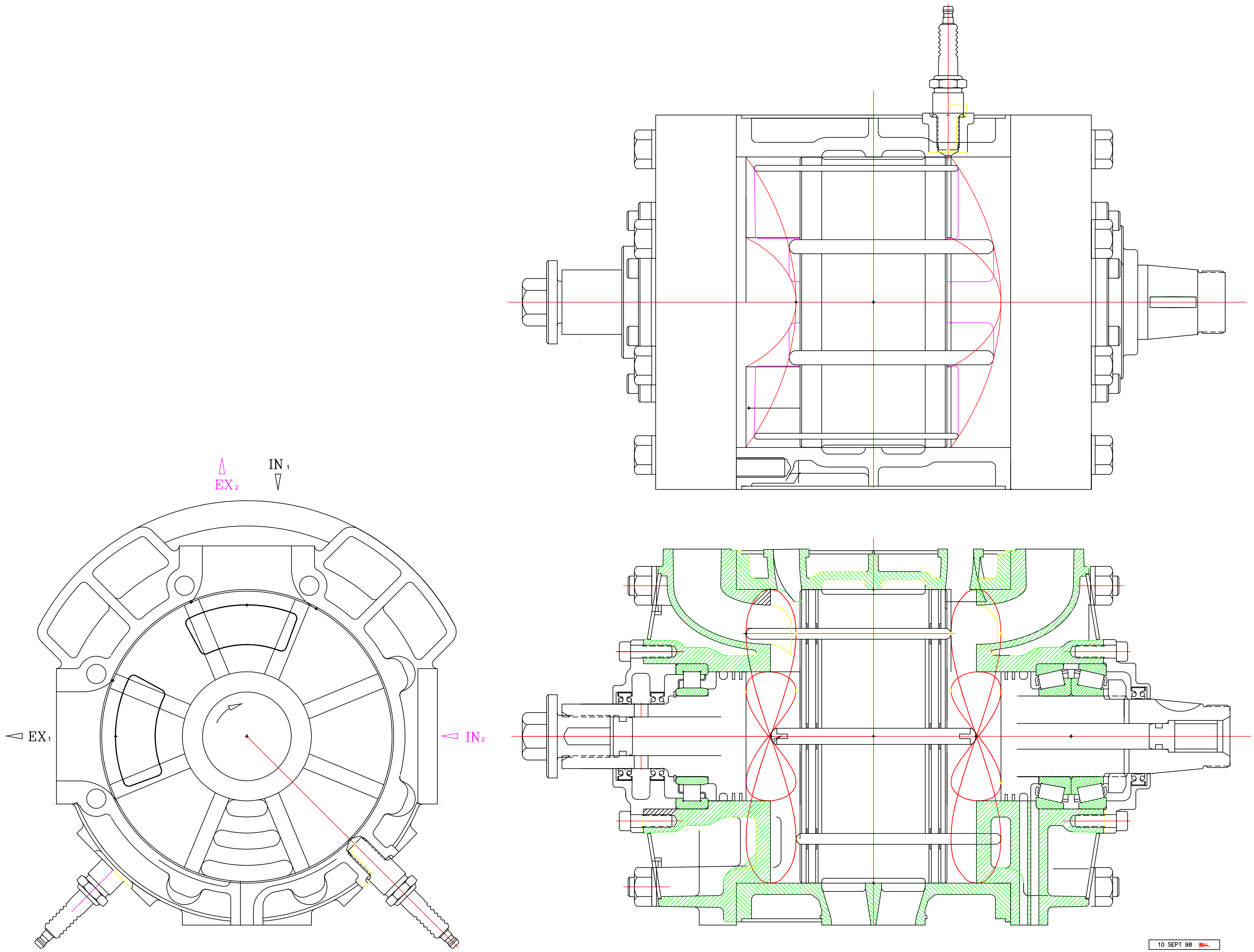






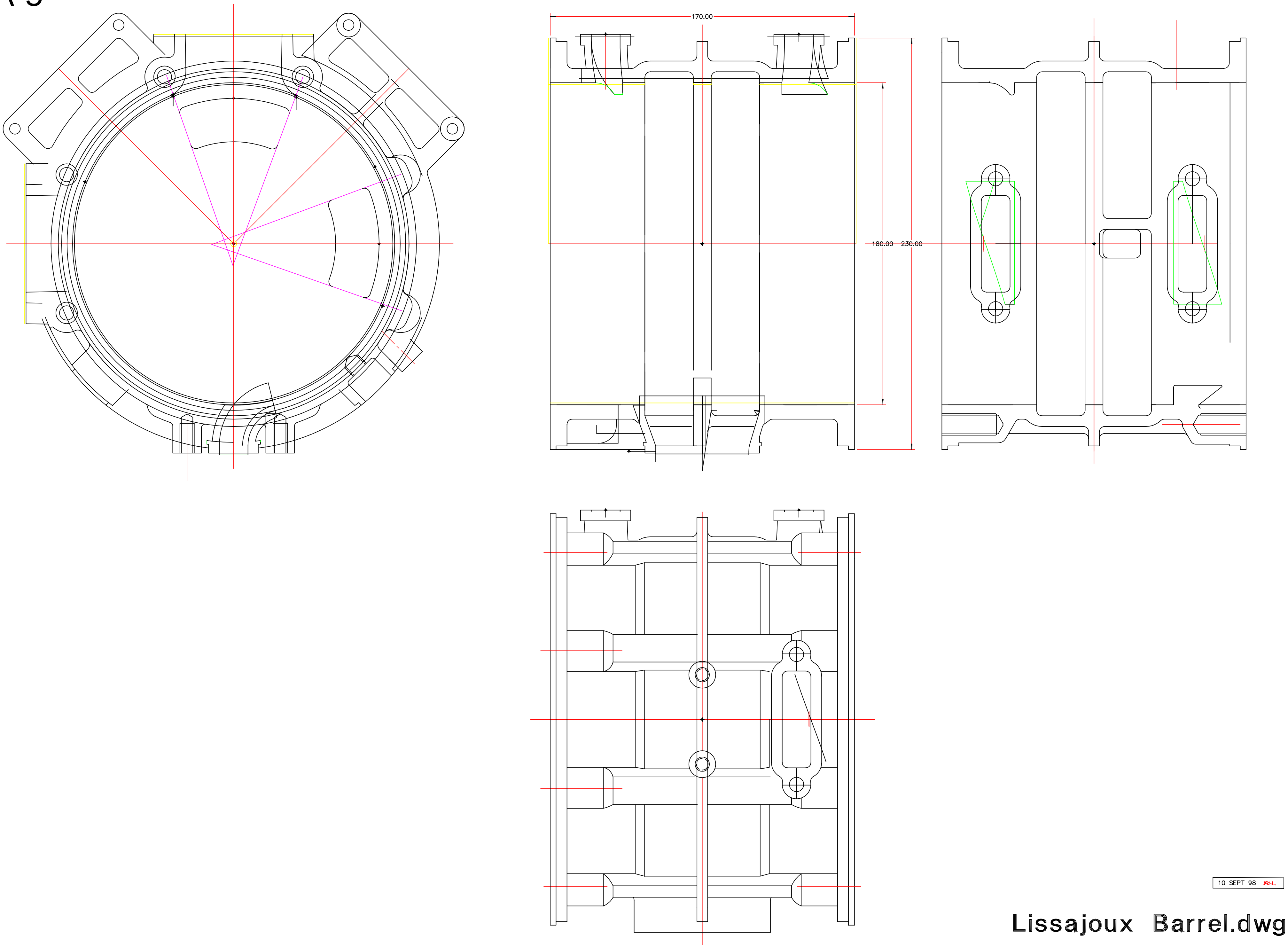
Lissajoux.dwg

A-4



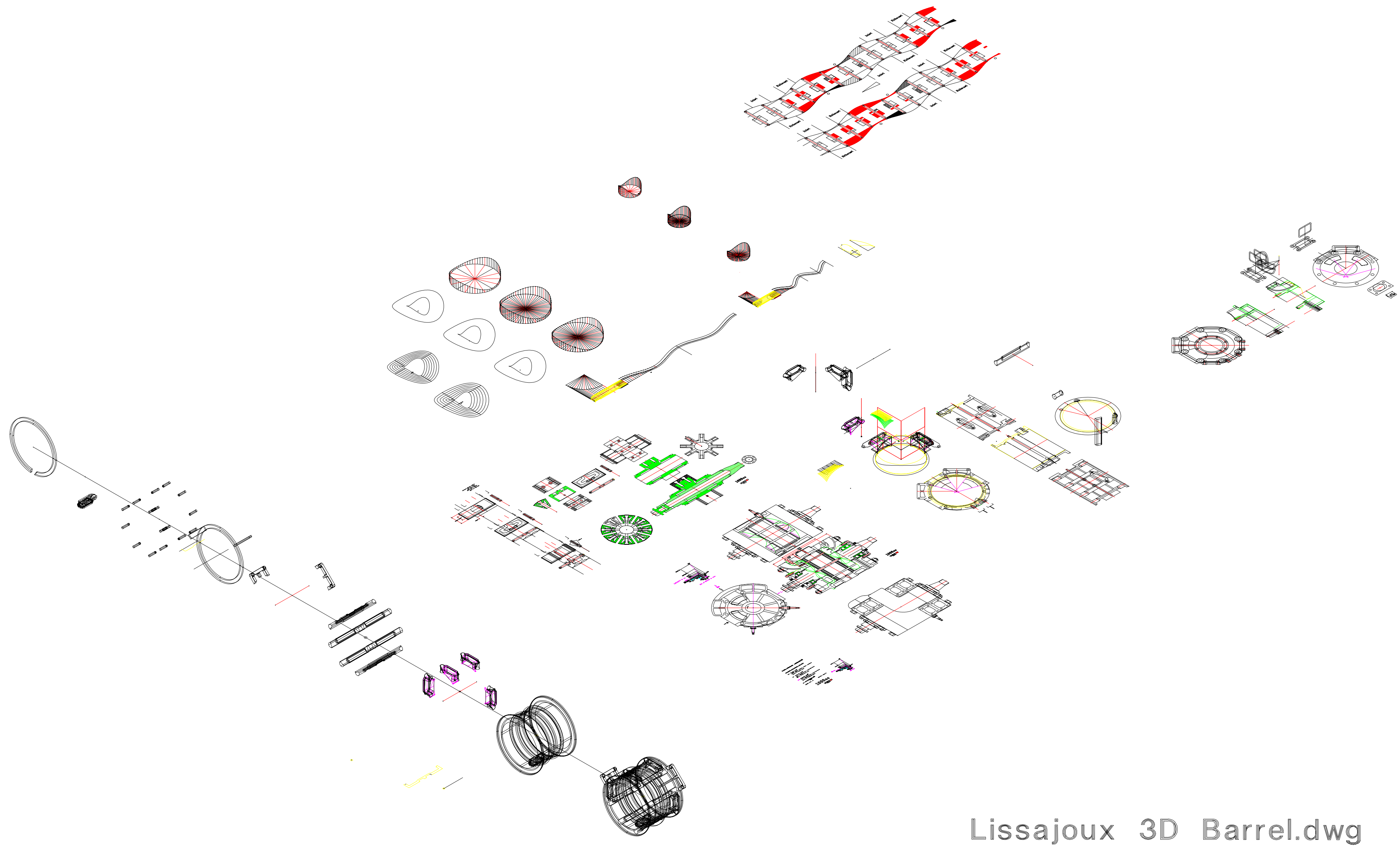
Lissajoux Layout.dwg

A-5



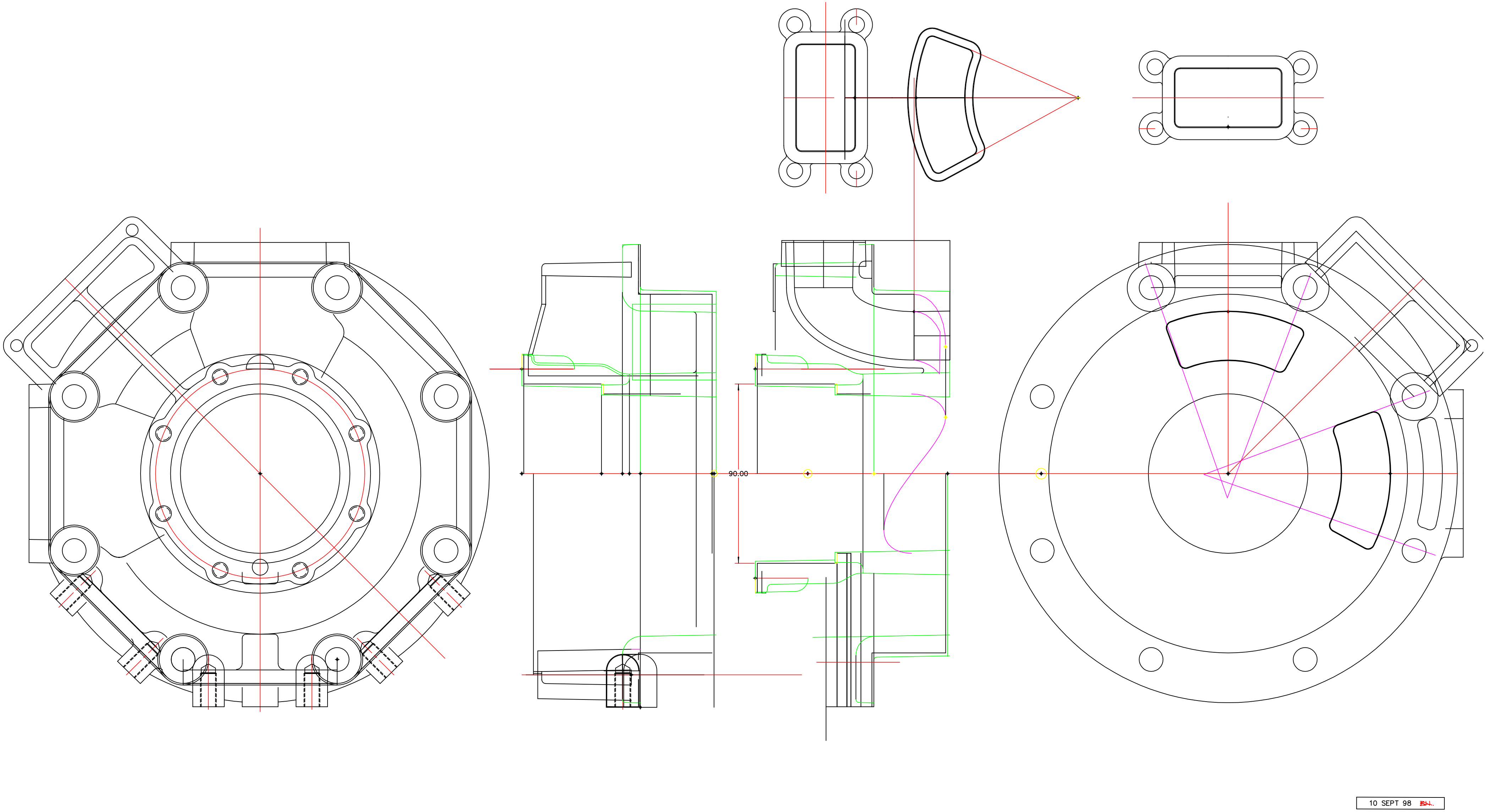
Lissajoux Barrel.dwg

A-6

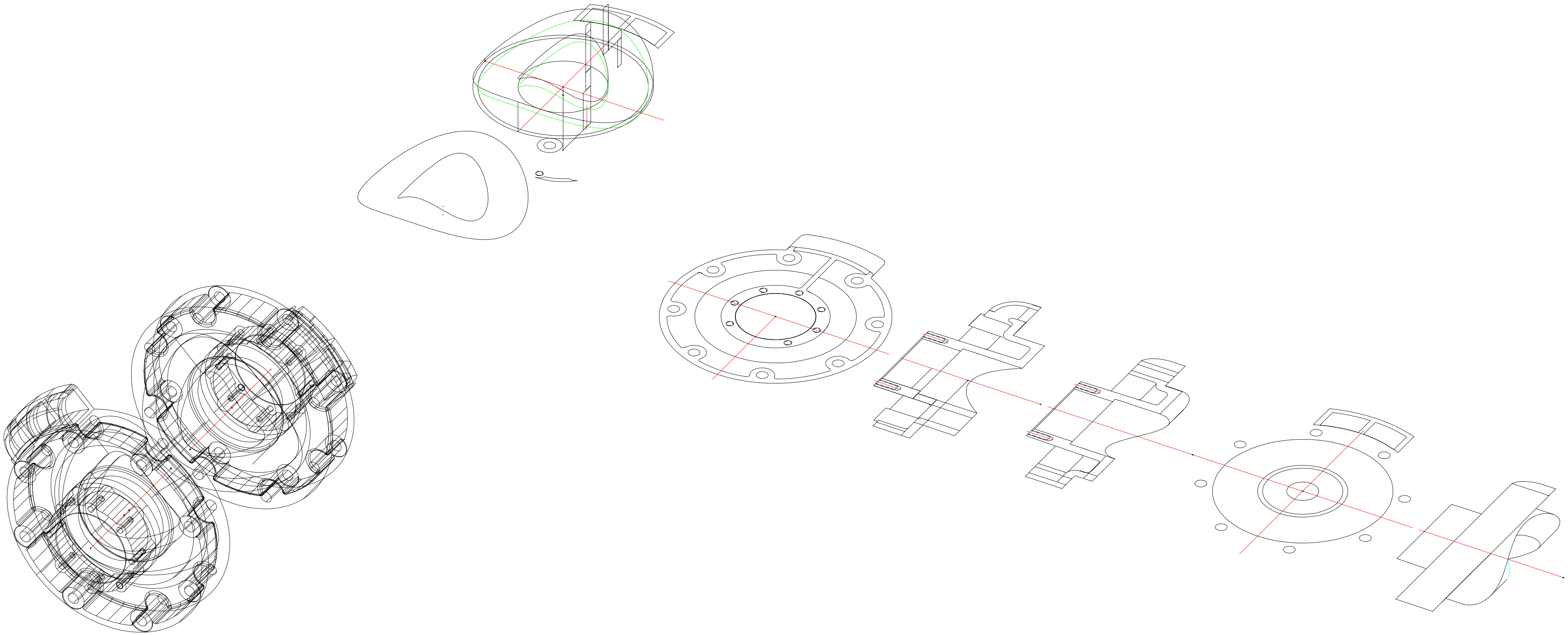


Lissajoux 3D Barrel.dwg

A-7

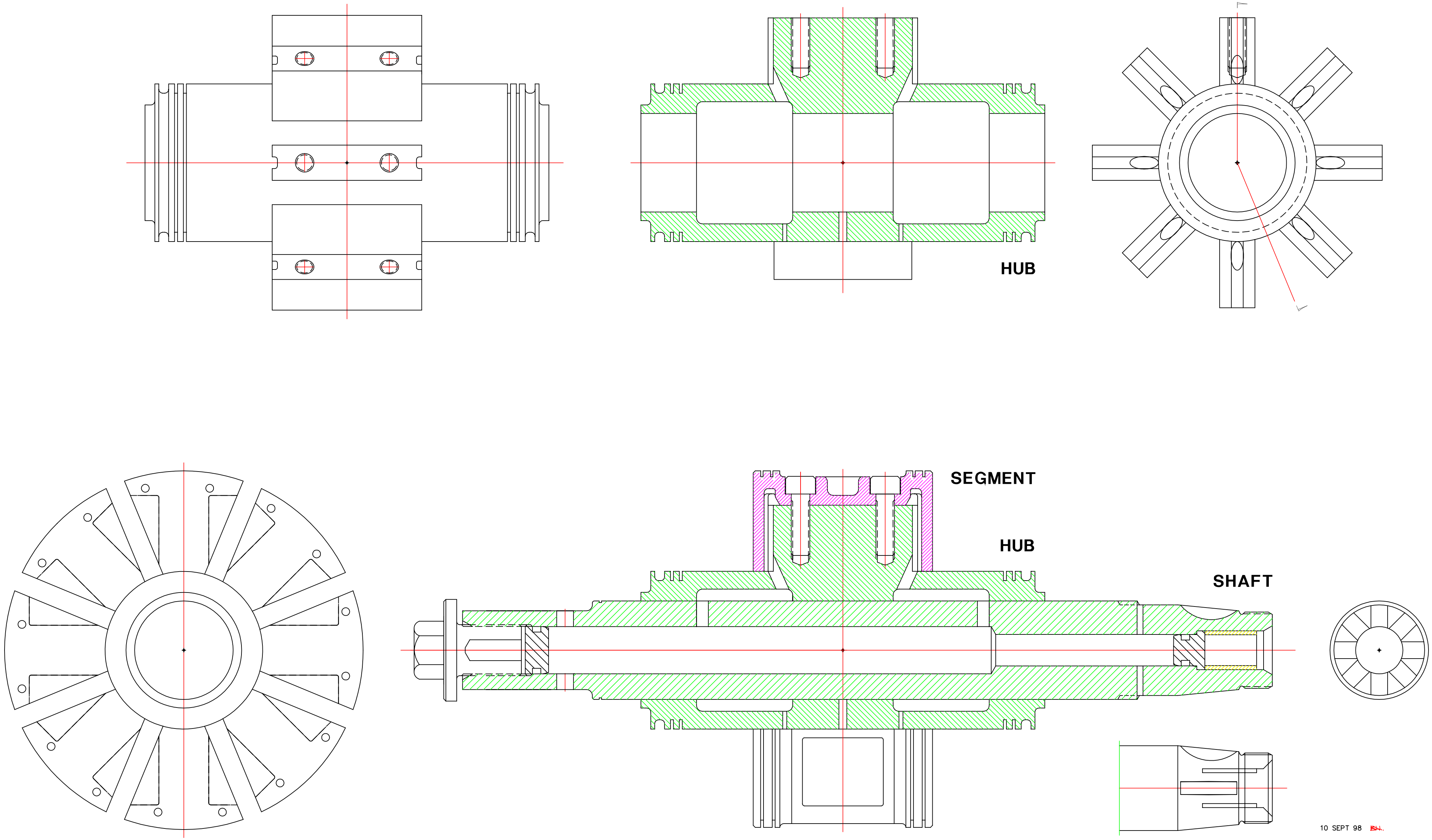


Lissajoux LH End.dwg

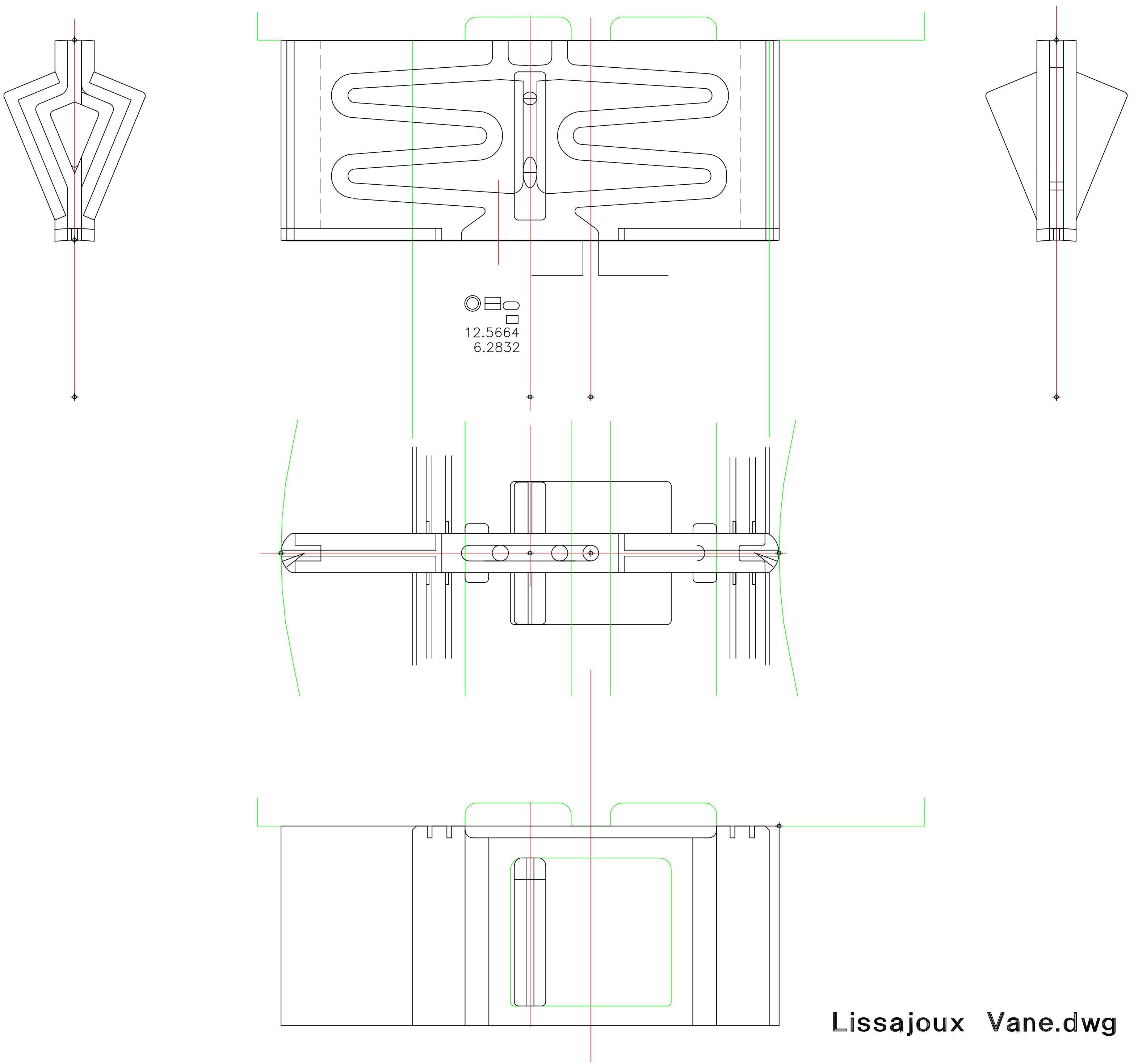


Lissajoux 3D Ends.dwg

A-9

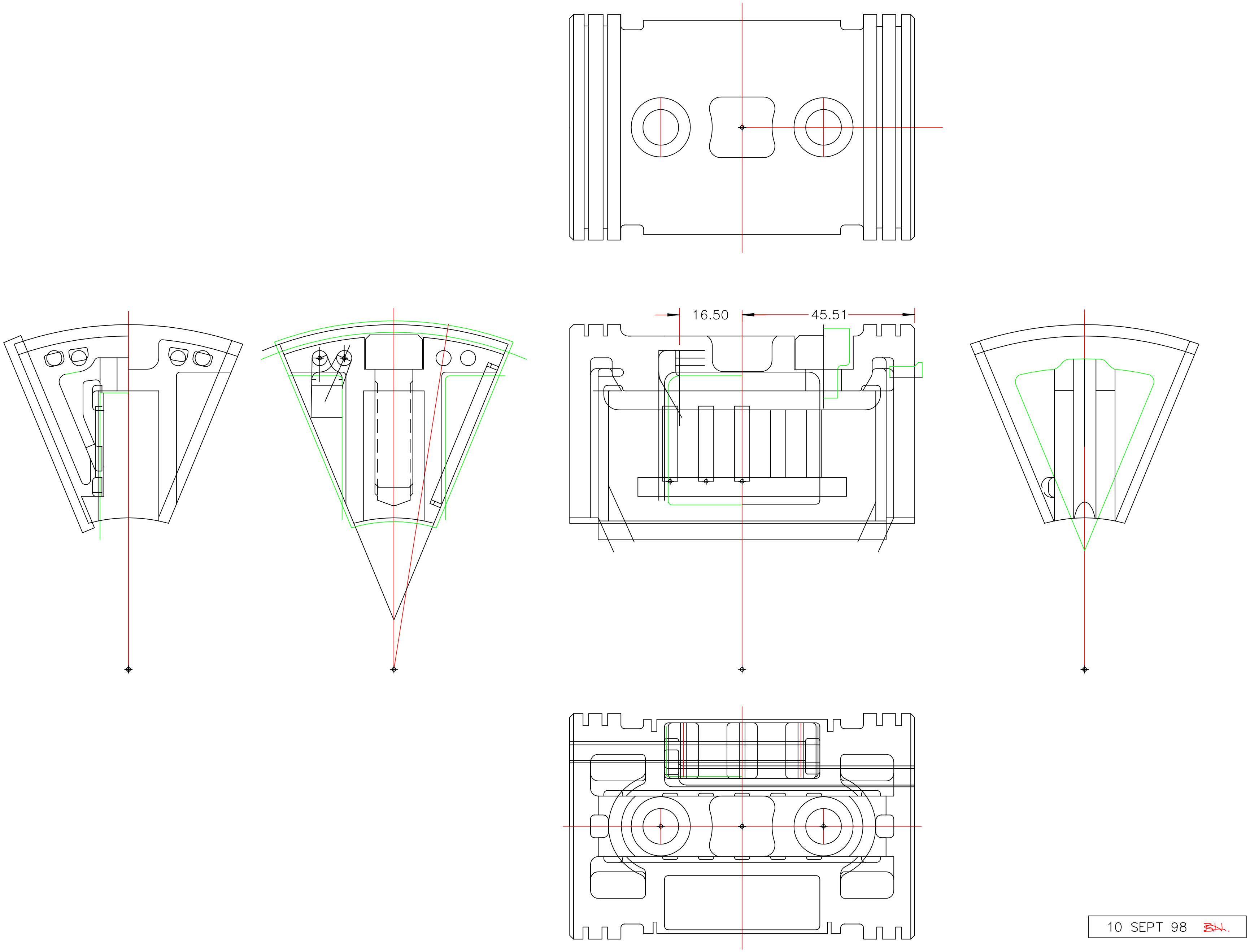


Lissajoux Shaft-Hub.dwg



Lissajoux Vane.dwg

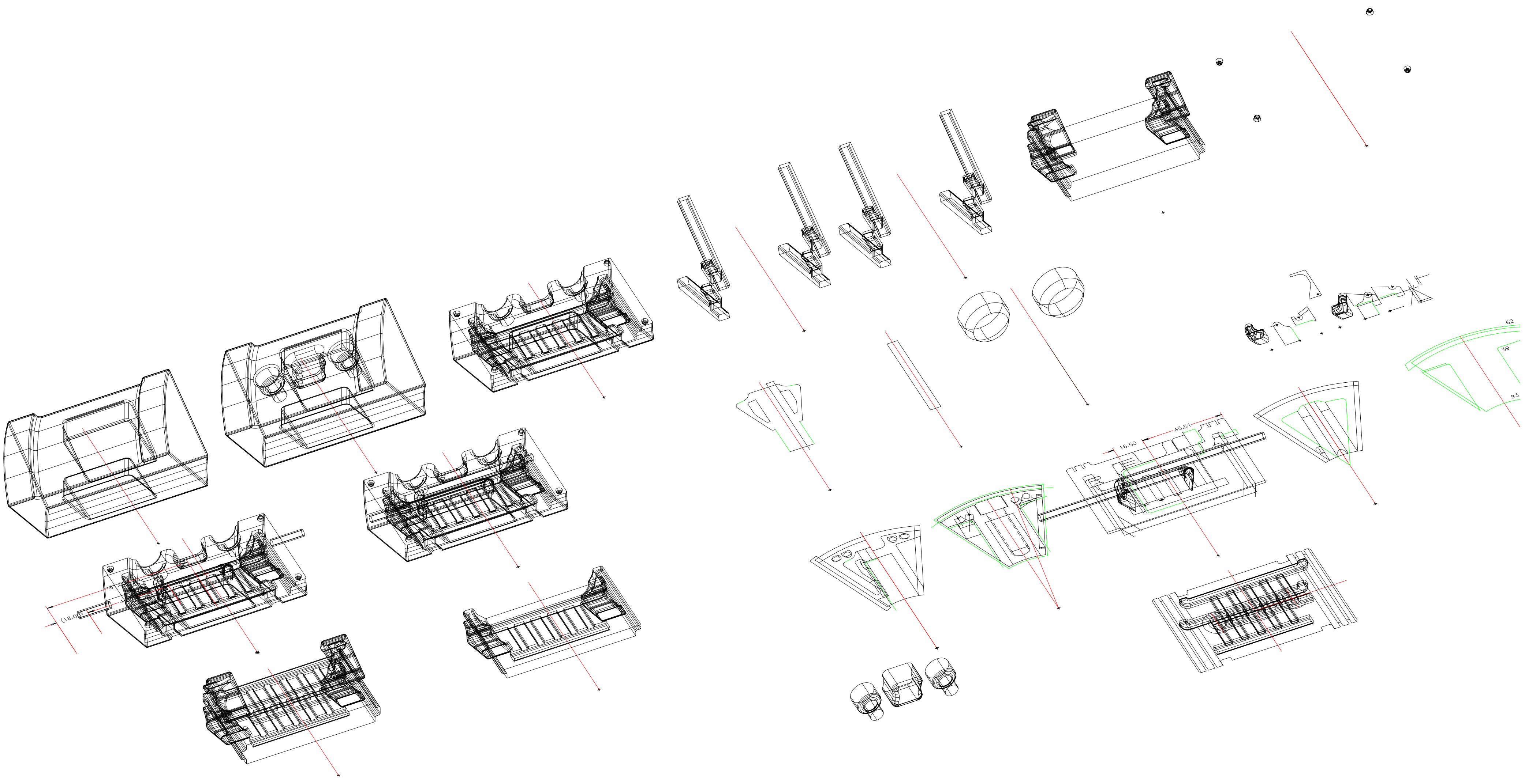
A-11



10 SEPT 98 BN.

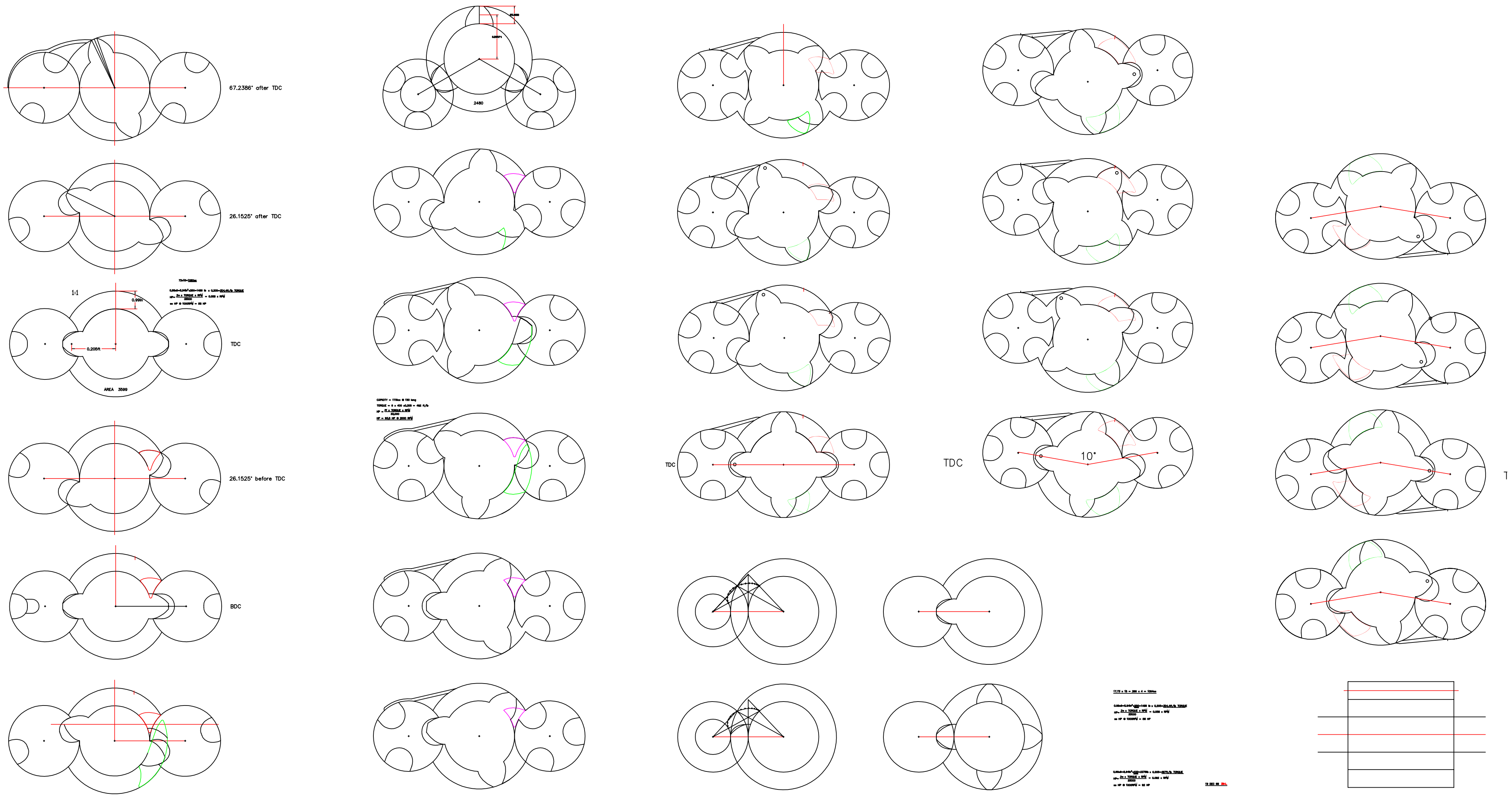
Lissajoux Segment.dwg

A-12



Lissajoux 3D Segment.dwg

B-1



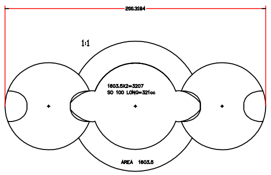
2 TEETH

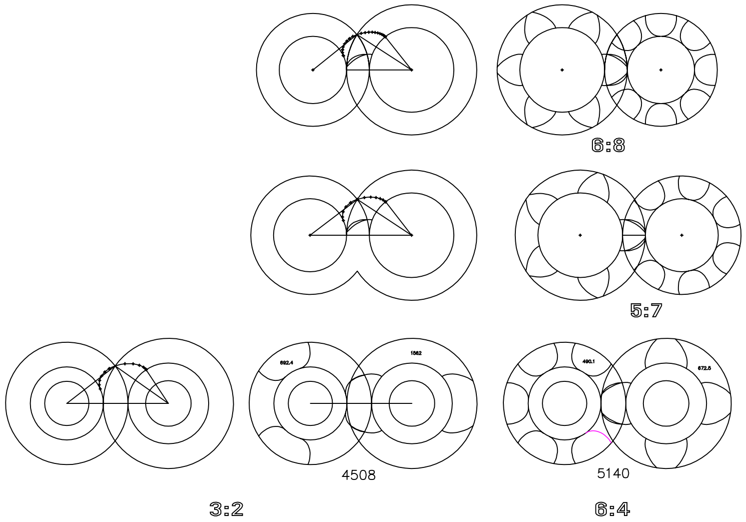
3 TEETH

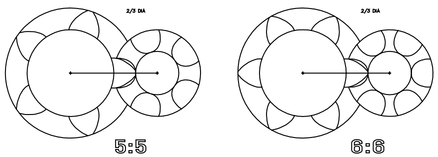
4 TEETH

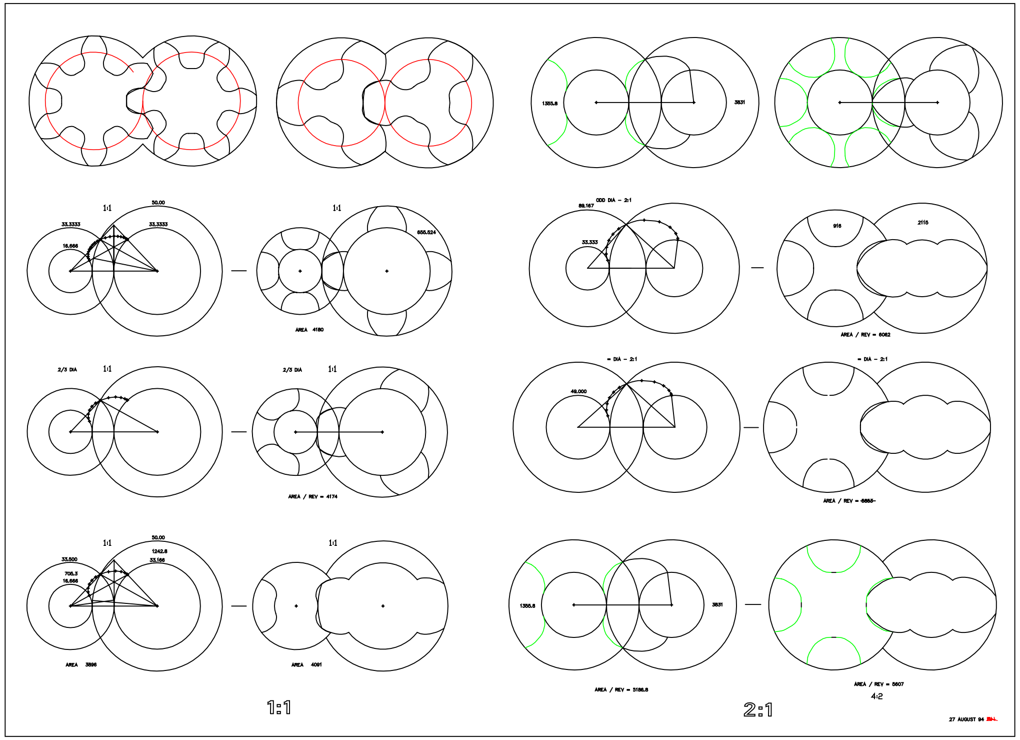
6-1.dwg

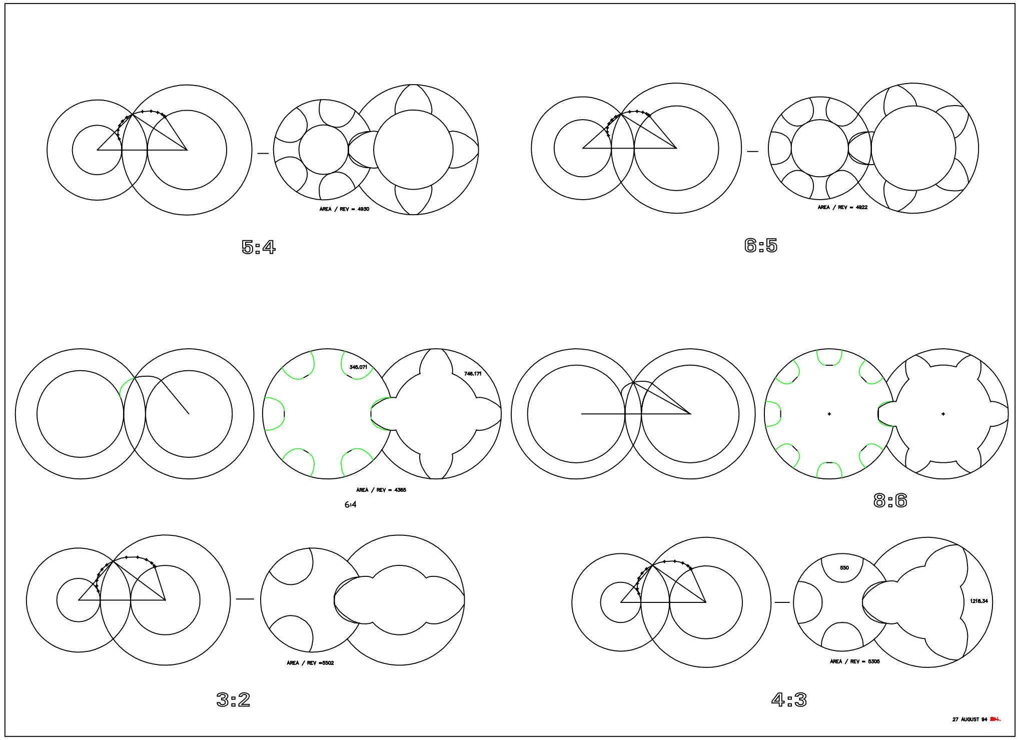
B-2





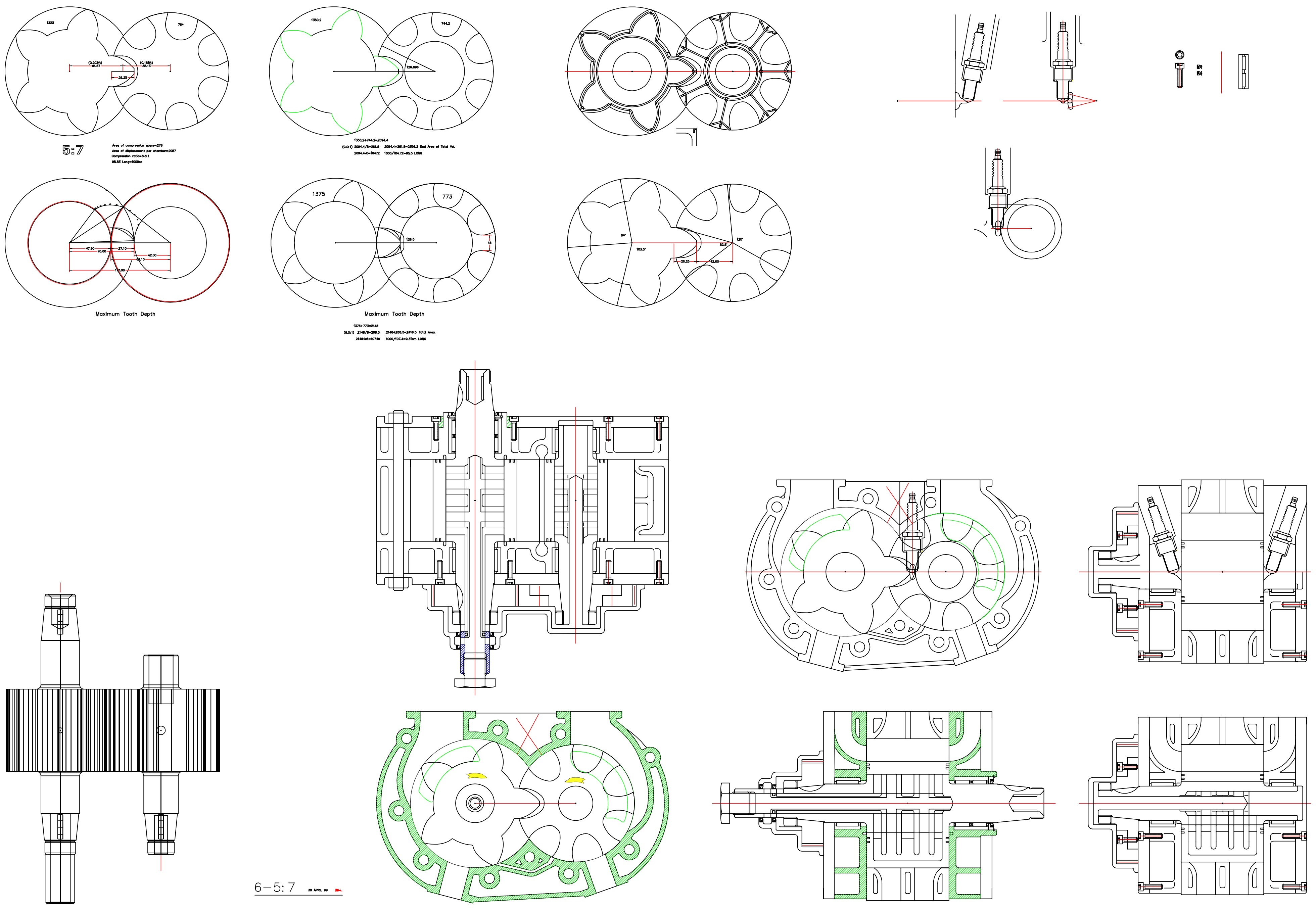






6 Ratios.dwg

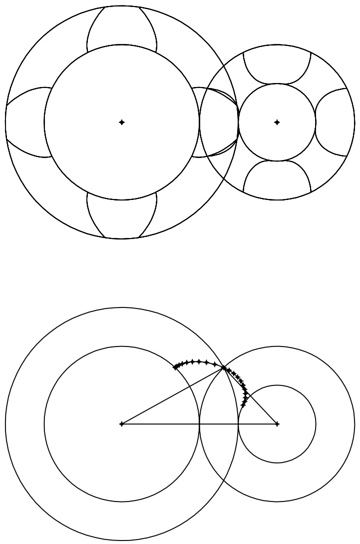
B-3

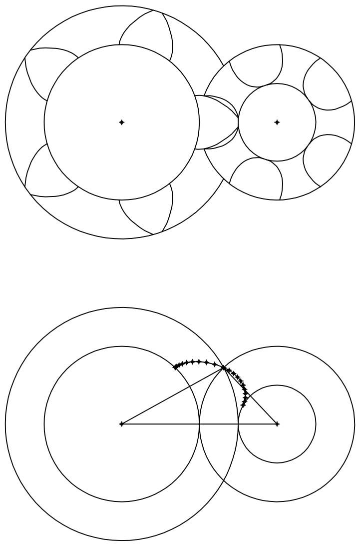


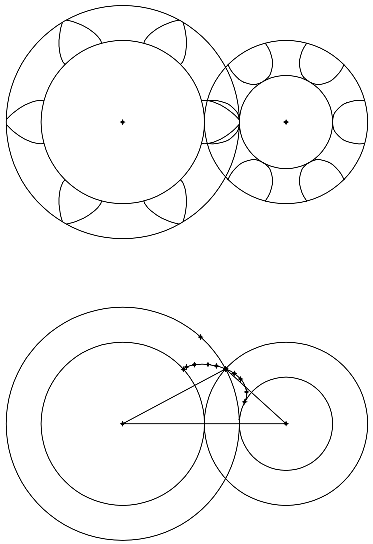
5:7
Area of compression space=278
Area of displacement per chamber=2087
Compression ratio=8.5:1
95.83 Long=1000cc
1350.2+744.2=2094.4
(9.0:1) 2094.4/8=261.8 2094.4+261.8=2356.2 End Area of Total Vol.
2094.4x5=10472 1000/104.72=95.5 LONG
1375
773
Maximum Tooth Depth
Maximum Tooth Depth
1375+773=2148
(9.0:1) 2148/8=268.5 2148+268.5=2416.5 Total Area.
21484x5=10740 1000/107.4=9.31cm LONG
6-5:7

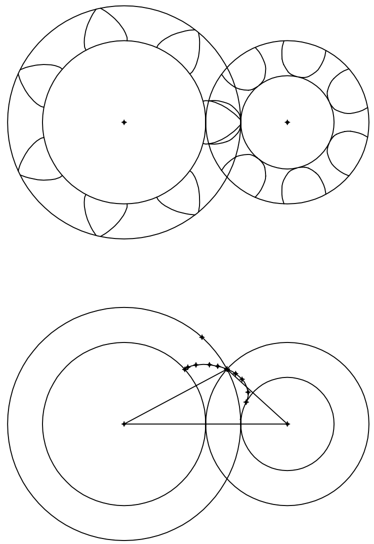
6-57.dwg

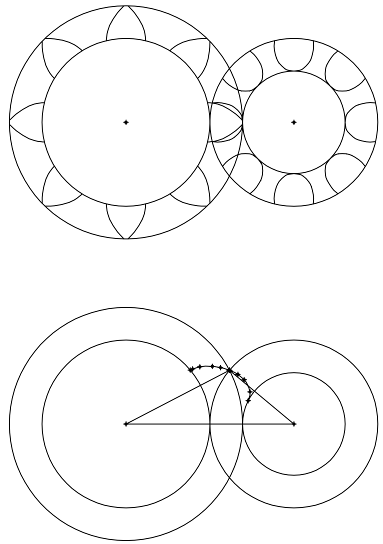
B-4


4:4


5:5

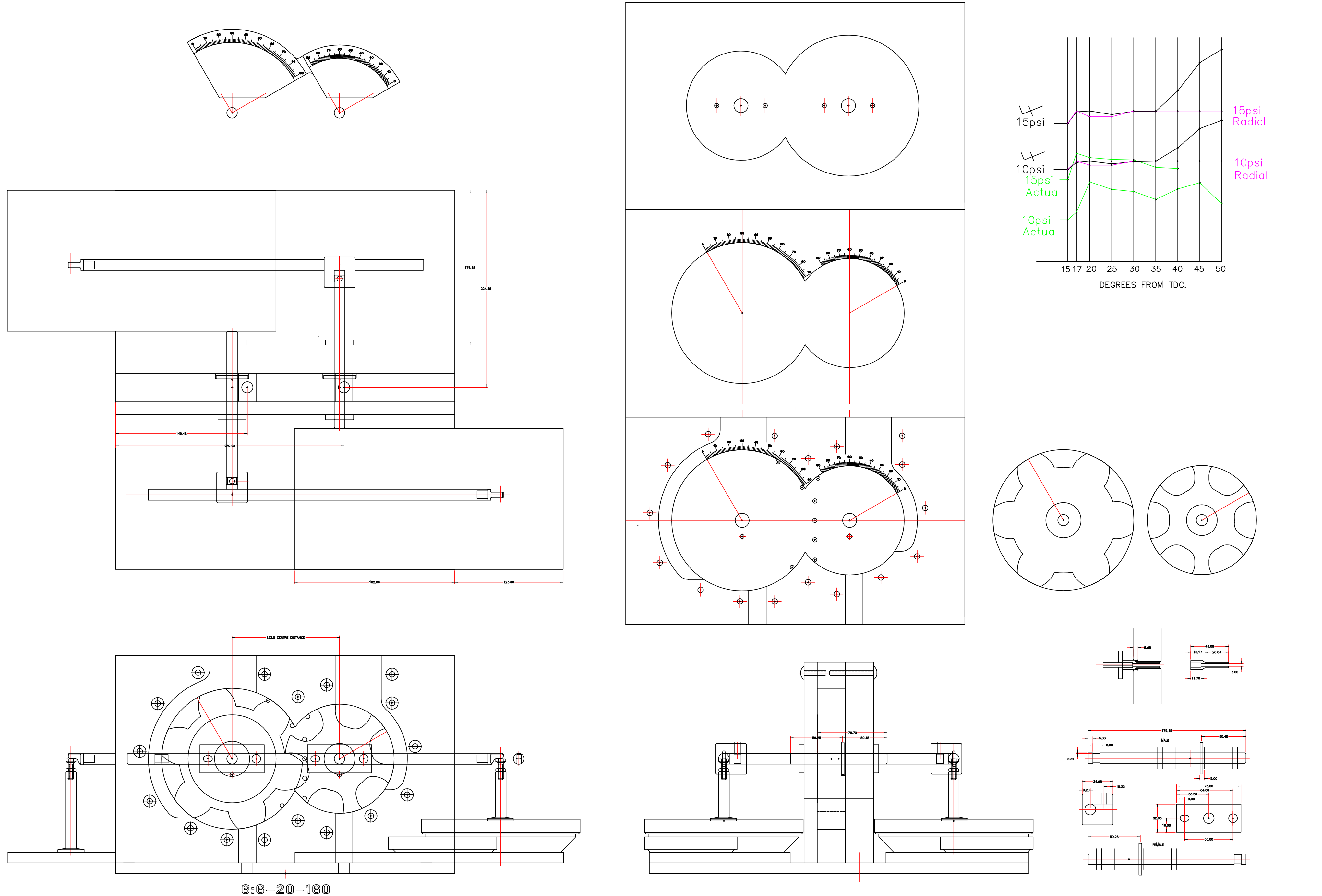

6:6


7:7


8:8

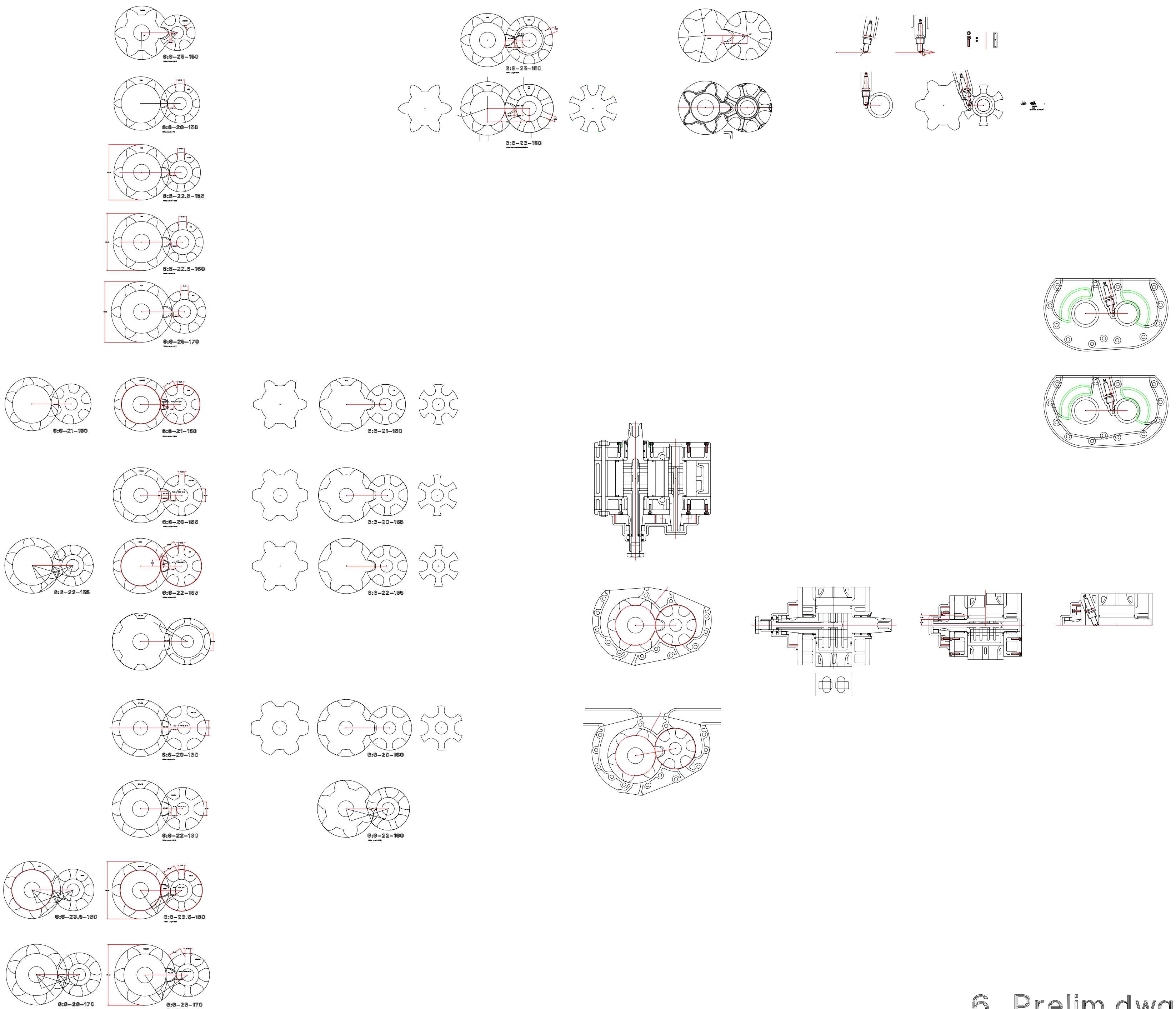
No of Teeth.dwg

B-5



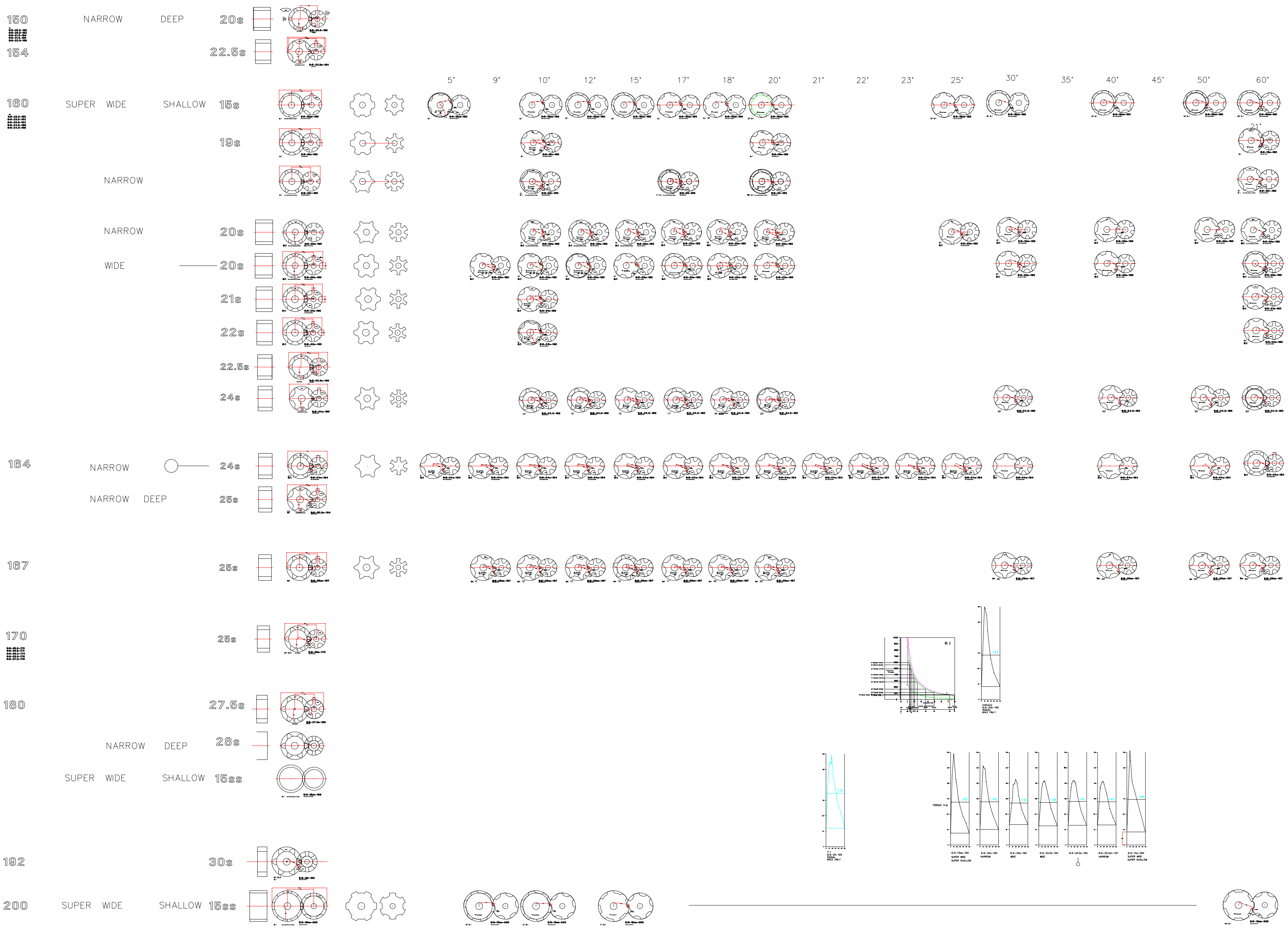
6 Test Rig.dwg

B-6



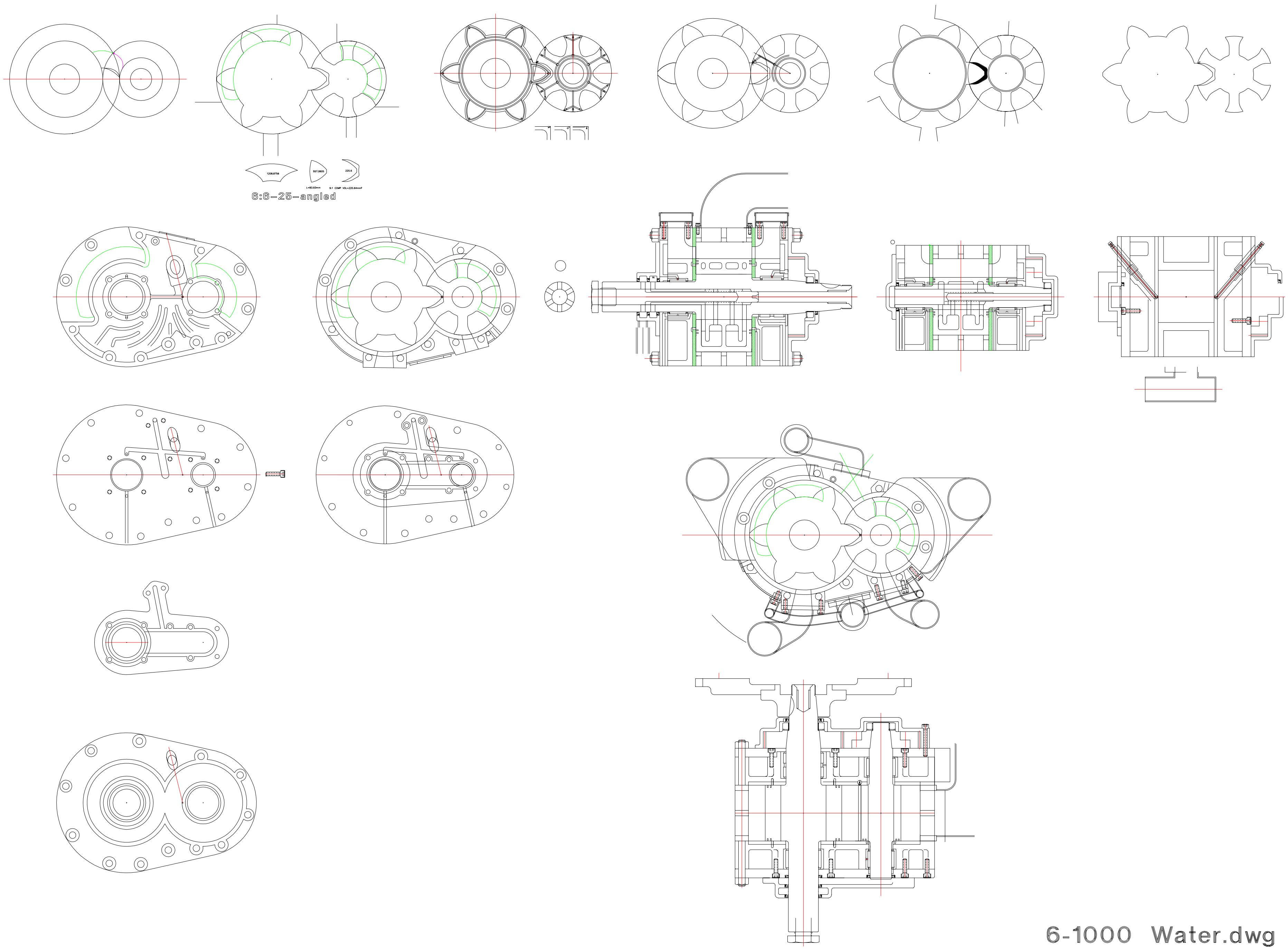
6 Prelim.dwg

B-7

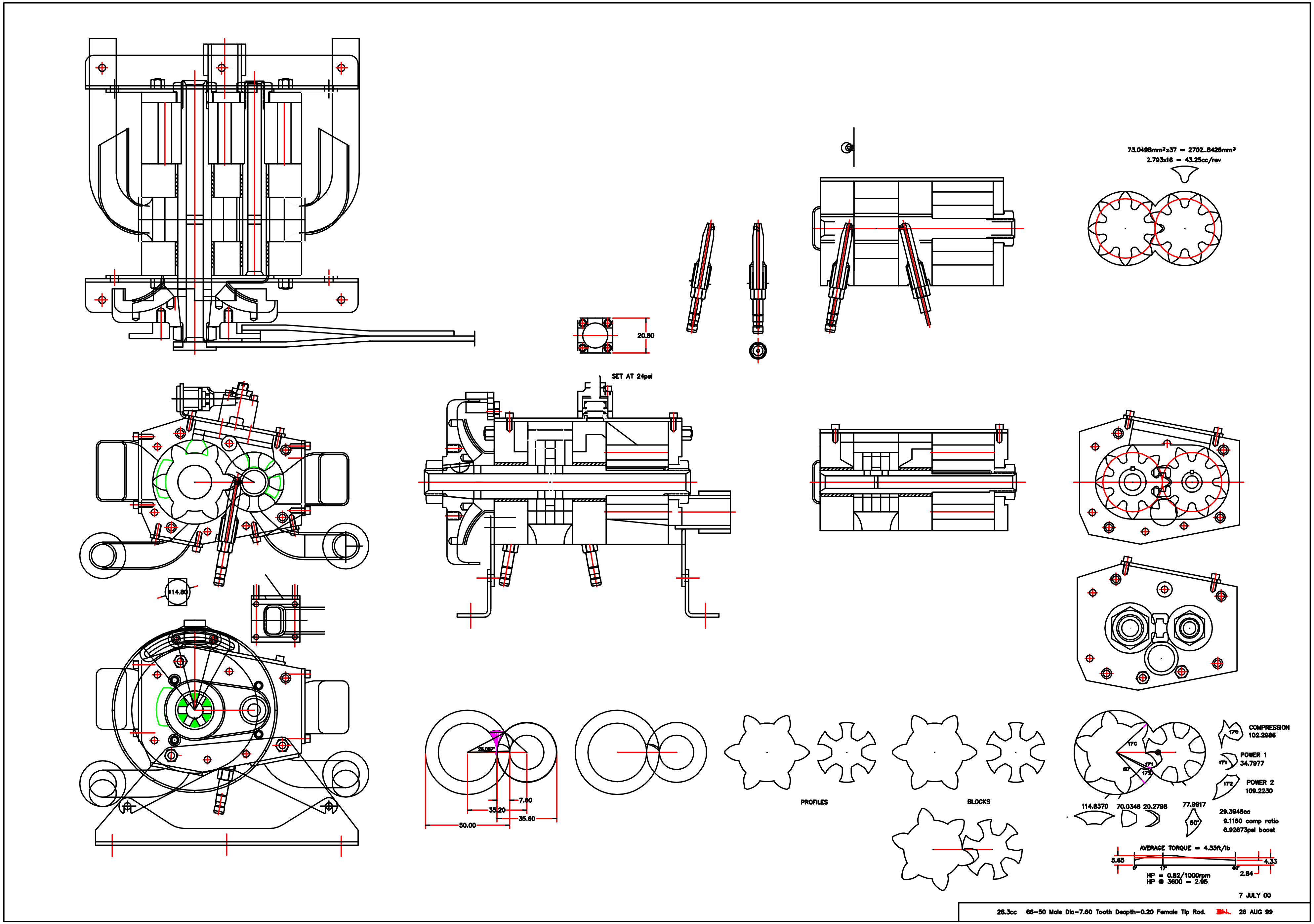


6 Proportion Investigation.dwg

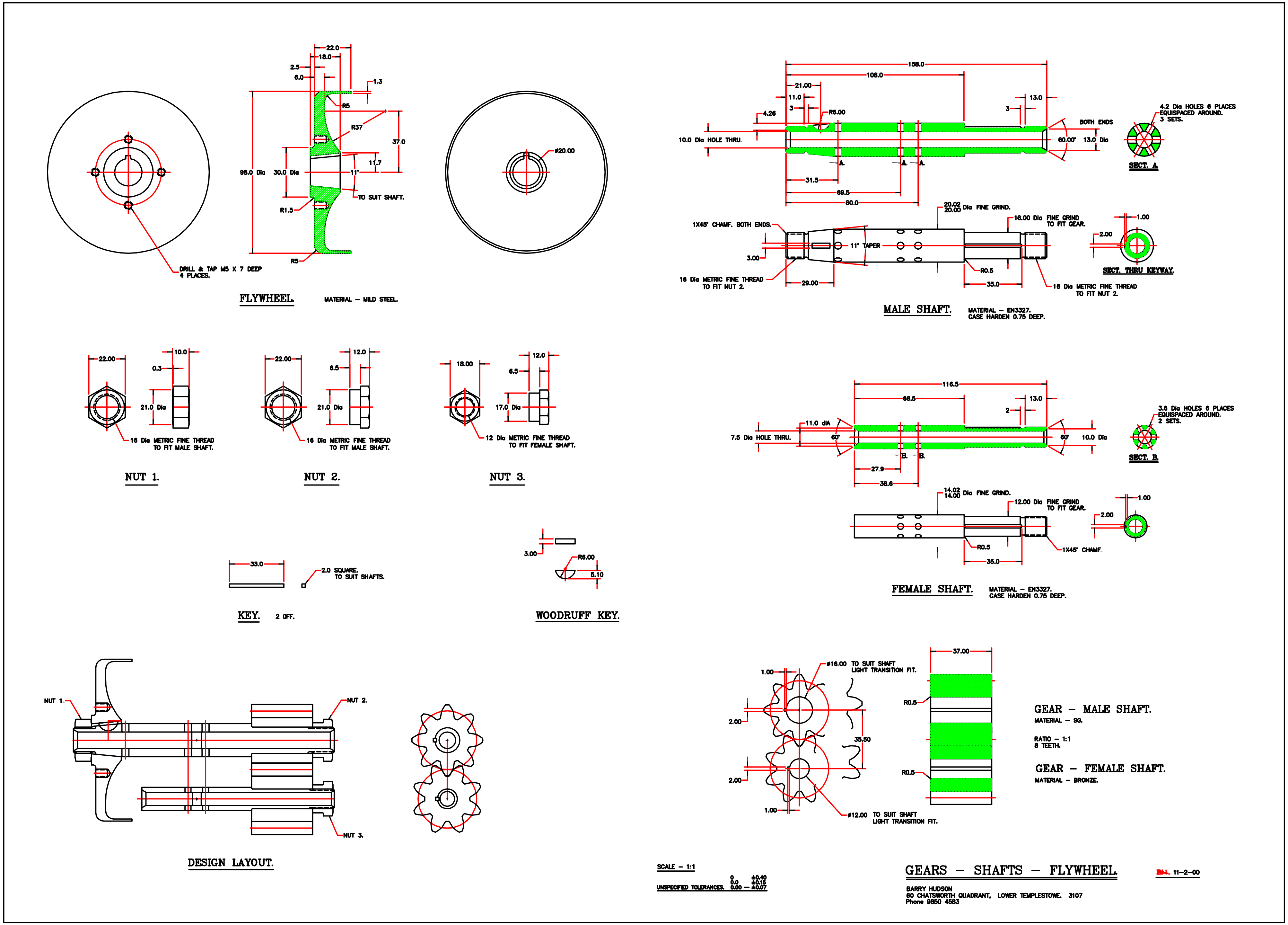
B-8

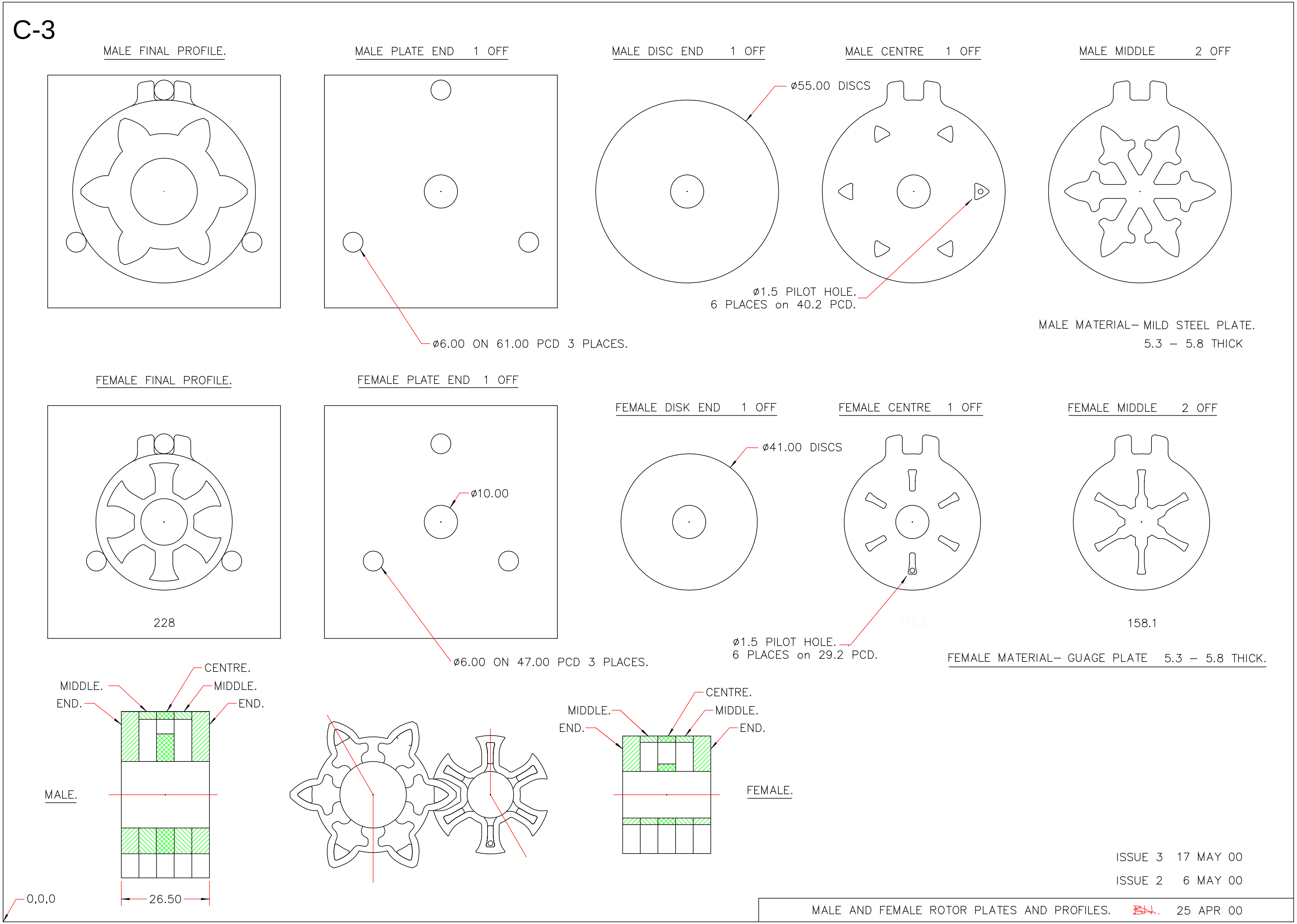


6-1000 Water.dwg

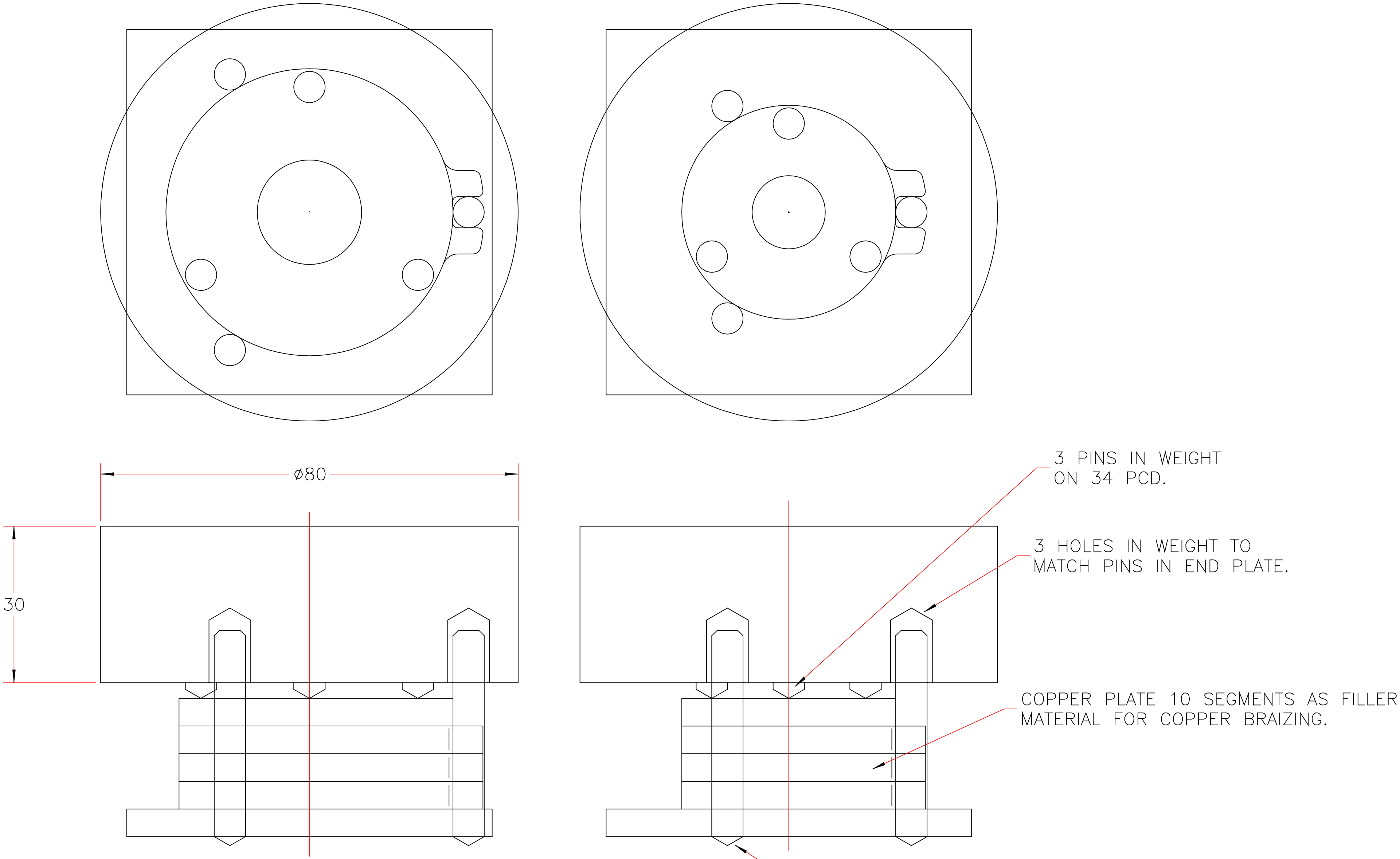


6-28 Layout.dwg

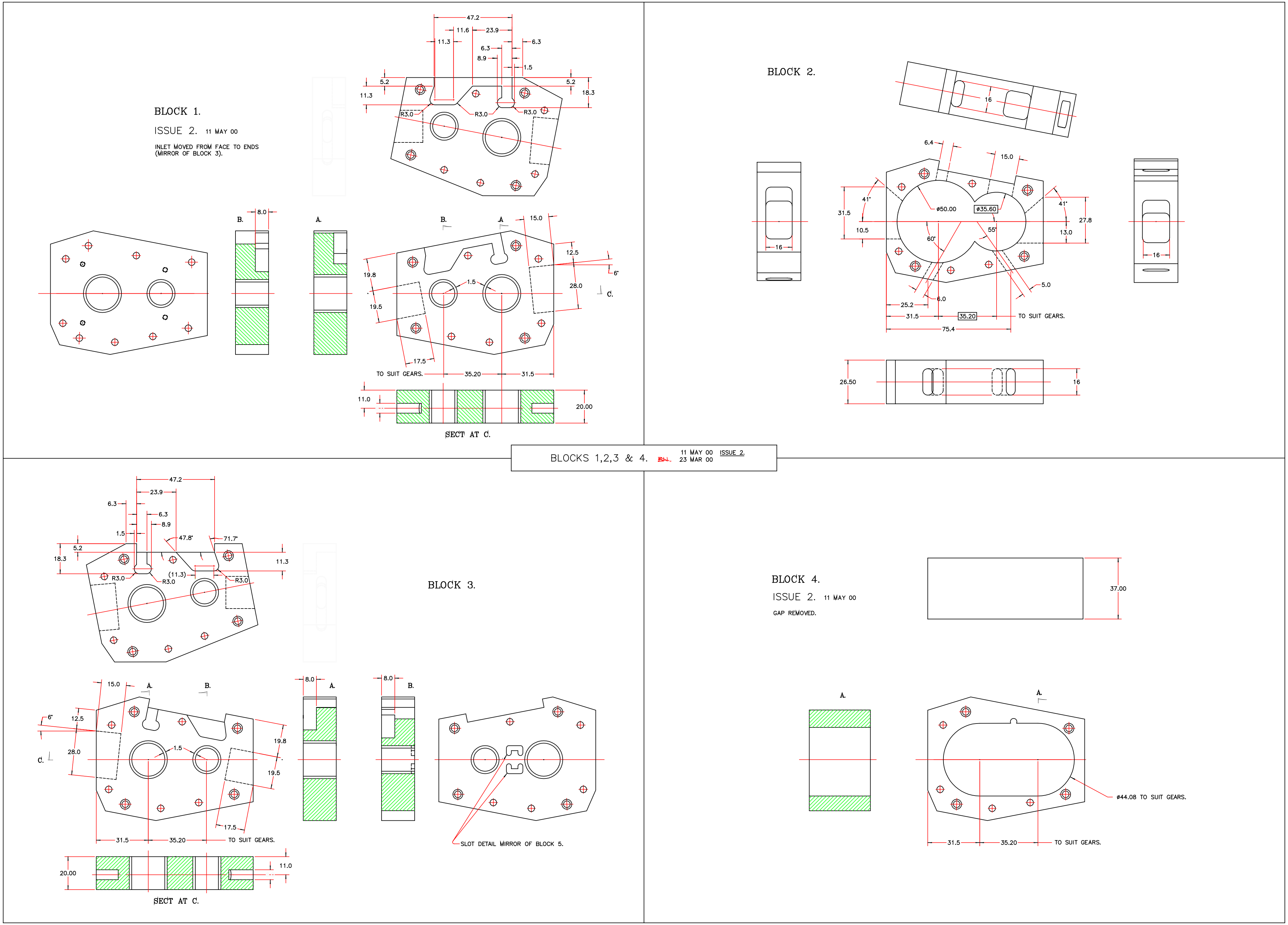

FLYWHEEL.
MATERIAL – MILD STEEL.
DRILL & TAP M5 X 7 DEEP 4 PLACES.
TO SUIT SHAFT.
MALE SHAFT.
MATERIAL – EN3327. CASE HARDEN 0.75 DEEP.
10.0 Dia HOLE THRU.
SECT. A.
4.2 Dia HOLES 6 PLACES EQUISPACED AROUND. 3 SETS.
1X45° CHAMF. BOTH ENDS.
16 Dia METRIC FINE THREAD TO FIT NUT 2.
SECT. THRU KEYWAY.
NUT 1.
NUT 2.
NUT 3.
16 Dia METRIC FINE THREAD TO FIT MALE SHAFT.
12 Dia METRIC FINE THREAD TO FIT FEMALE SHAFT.
KEY. 2 OFF.
2.0 SQUARE. TO SUIT SHAFTS.
WOODRUFF KEY.
FEMALE SHAFT.
MATERIAL – EN3327. CASE HARDEN 0.75 DEEP.
7.5 Dia HOLE THRU.
SECT. B.
3.6 Dia HOLES 6 PLACES EQUISPACED AROUND. 2 SETS.
DESIGN LAYOUT.
GEAR – MALE SHAFT.
MATERIAL – SG.
RATIO – 1:1
8 TEETH.
GEAR – FEMALE SHAFT.
MATERIAL – BRONZE.
ø16.00 TO SUIT SHAFT LIGHT TRANSITION FIT.
ø12.00 TO SUIT SHAFT LIGHT TRANSITION FIT.
SCALE – 1:1
UNSPECIFIED TOLERANCES.
GEARS – SHAFTS – FLYWHEEL.
BARRY HUDSON
60 CHATSWORTH QUADRANT, LOWER TEMPLESTOWE. 3107
Phone 9850 4583
11-2-00



6-28 Wire Cutting Profiles.dwg



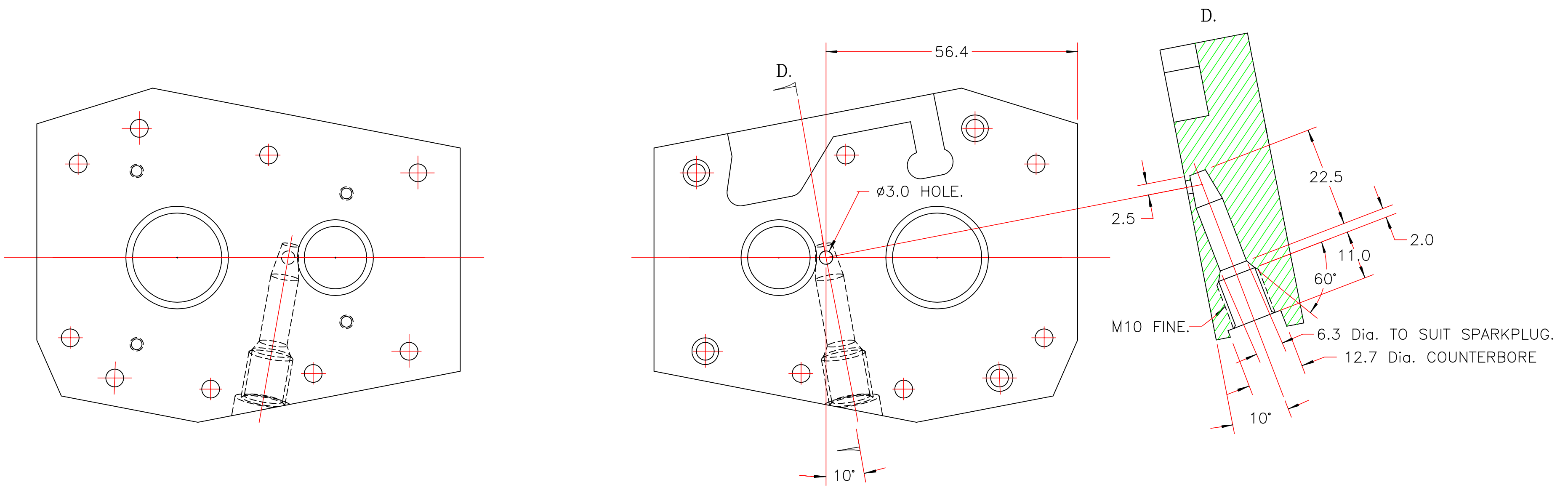
COPPER BRAIZING SETUP.



6-28 Blocks 1 2 3 & 4.dwg

C-6

BLOCK 1.



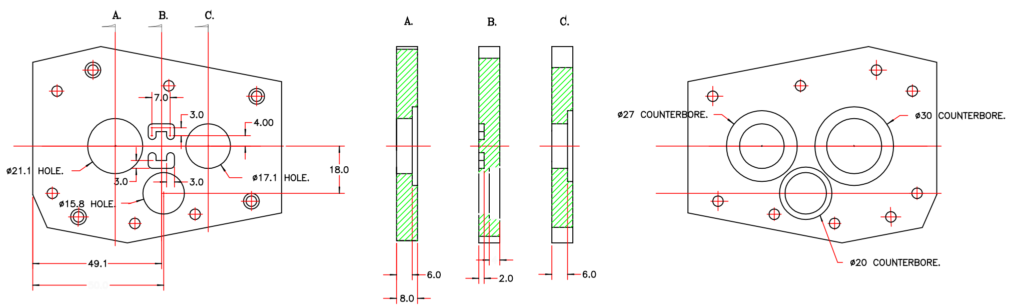
BLOCK 3. IS MIRROR IMAGE OF BLOCK 1.

SPARKPLUG HOLE DETAIL IN BLOCKS 1 AND 3. B.N. 23 MAR 00

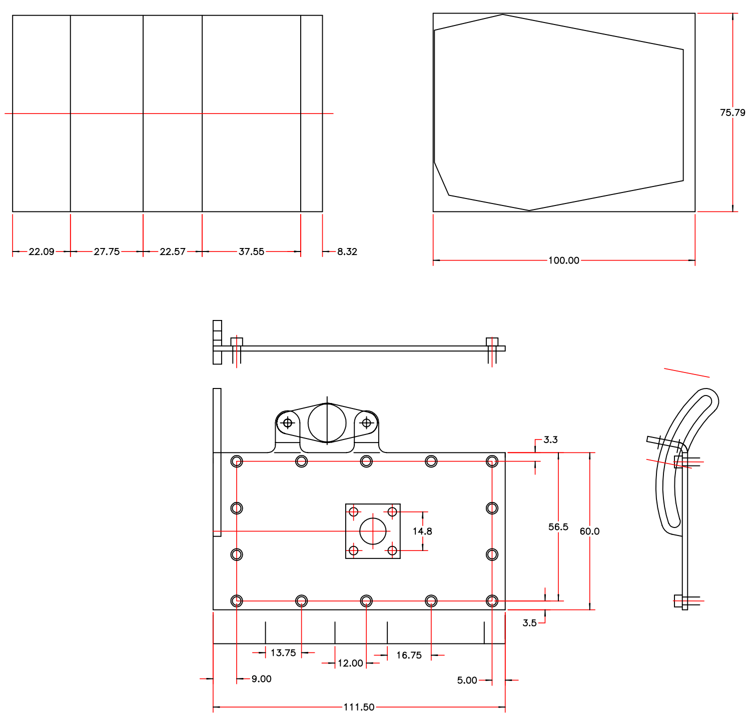
6-28 Spark Plug Hole Detail.dwg

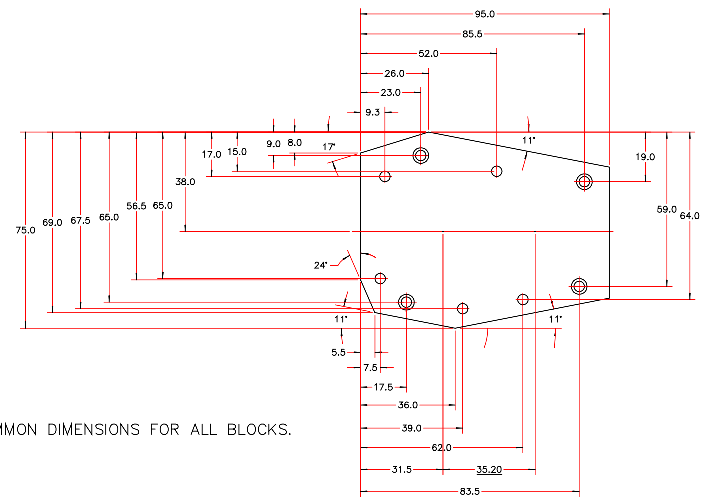
C-7

BLOCK 5.

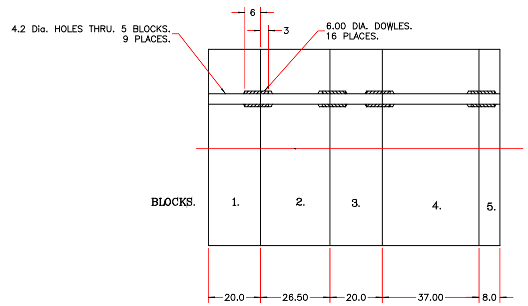


BLOCK 5.	BH.	23 MAR 00





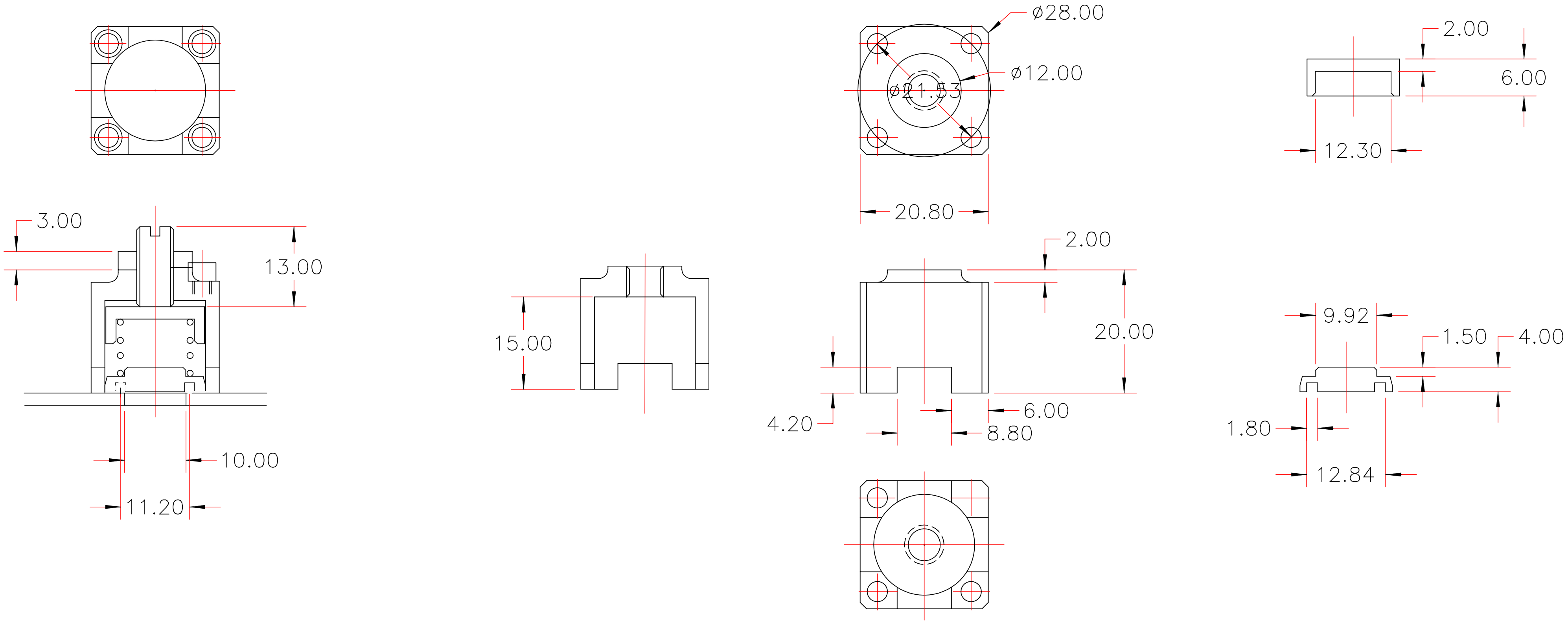
COMMON DIMENSIONS FOR ALL BLOCKS.



UNSPECIFIED TOLERANCES.	
0	±0.5
0.0	±0.20
0.00	±0.10

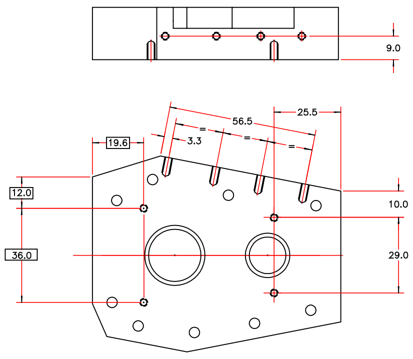
COMMON ELEMENTS.	BH.	23 MAR 00

6-28 Block 5.dwg

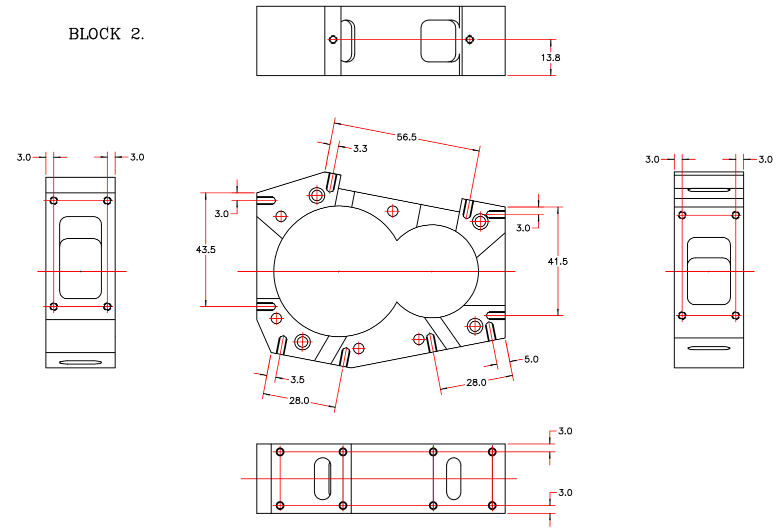


6-28 Relief Valve.dwg

BLOCK 1.

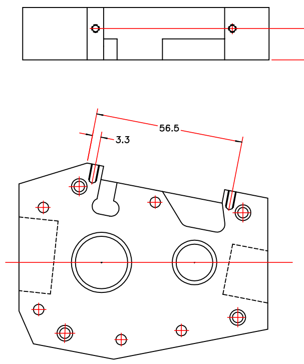


BLOCK 2.

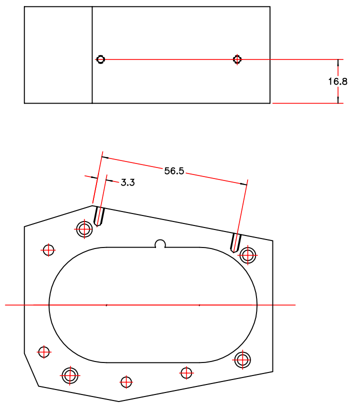


PLACEMENT OF M3 x 6 (EFFECTIVE DEPTH) TAPPED HOLES. 34 PLACES IN 5 BLOCKS. 23 MAR 00

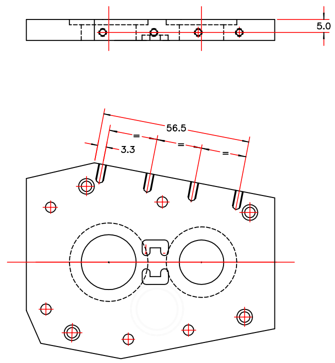
BLOCK 3.



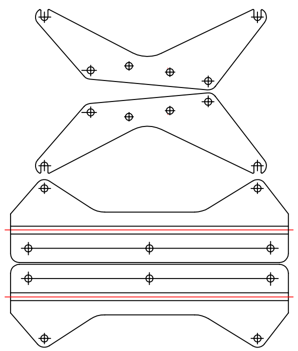
BLOCK 4.

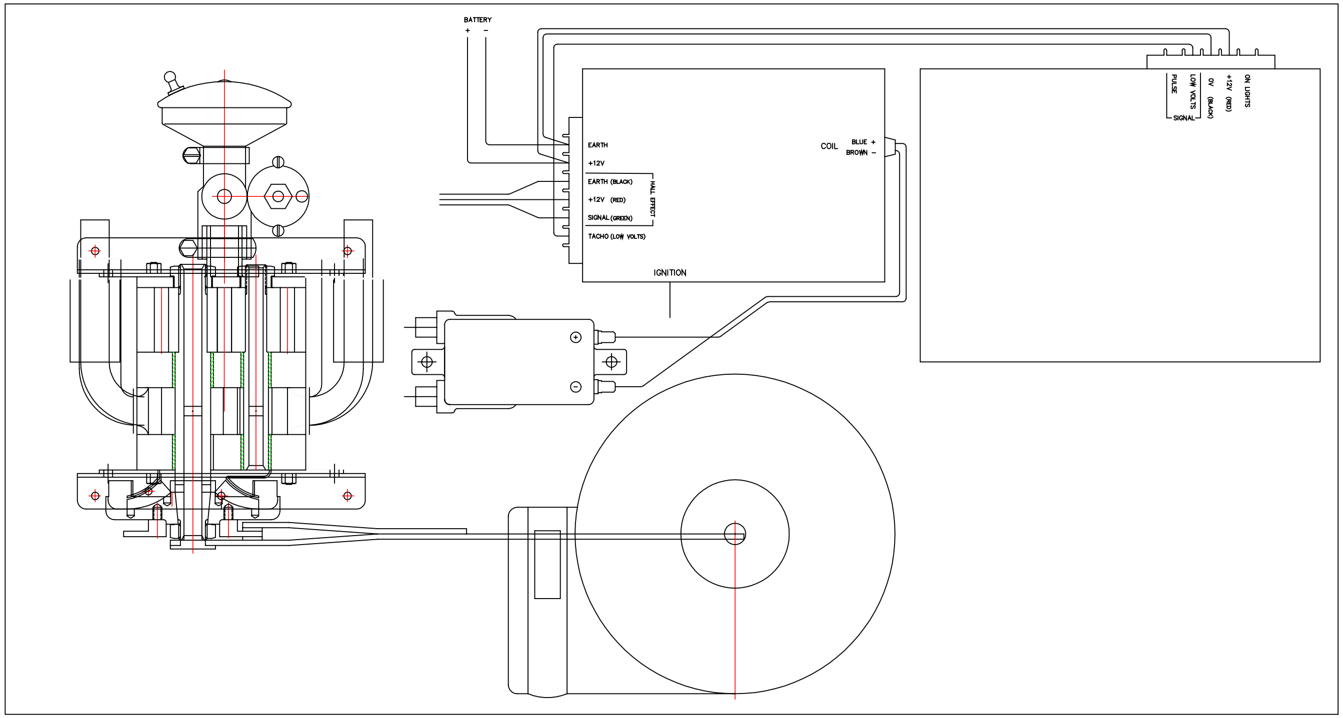


BLOCK 5.

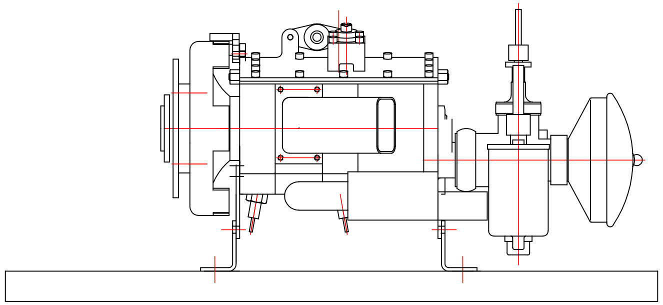


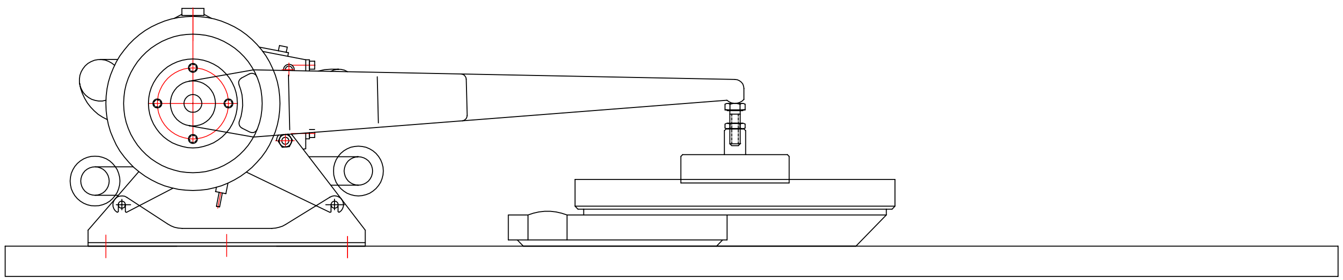
C-10





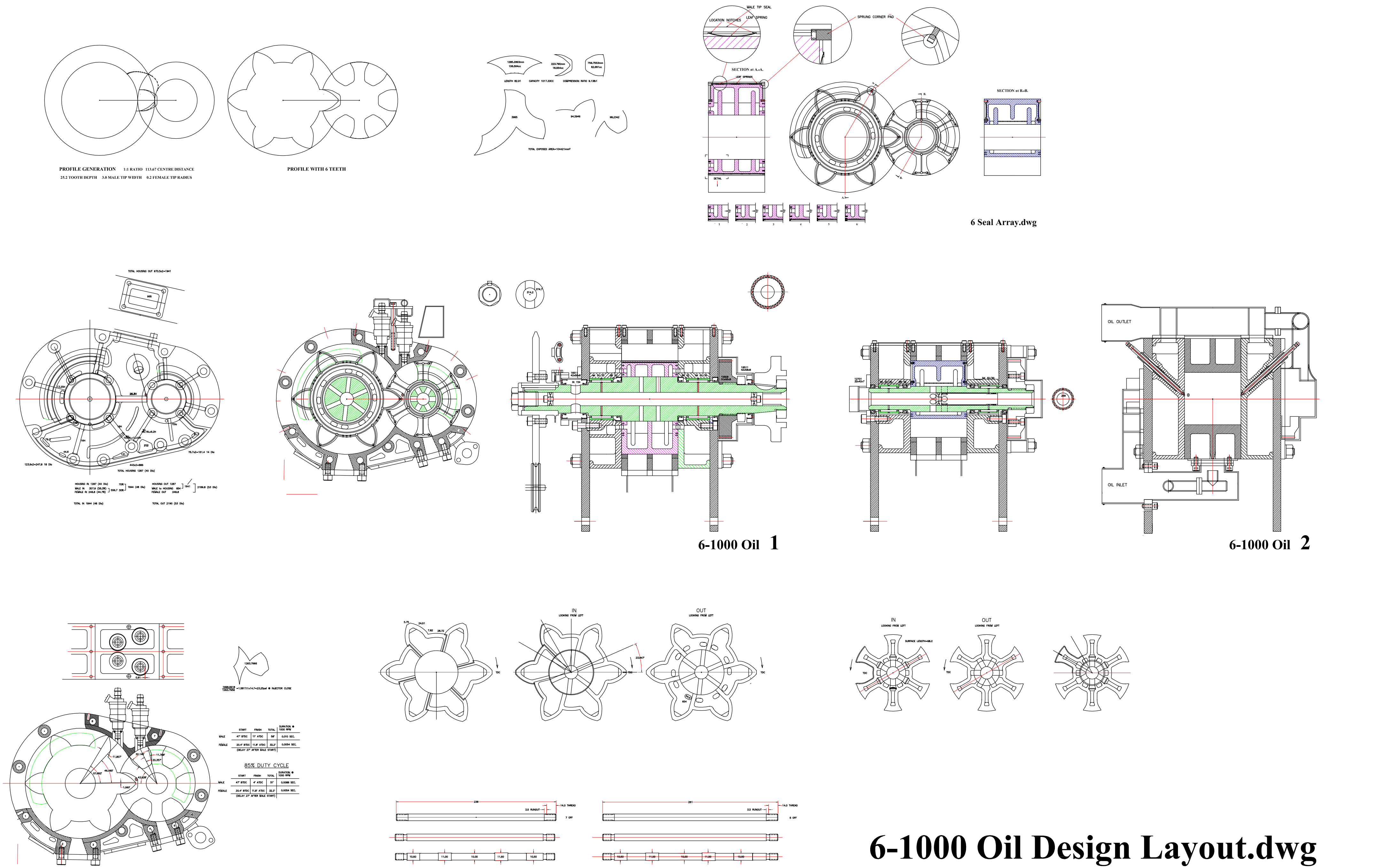
6-28 Pressure Relief Valve.dwg





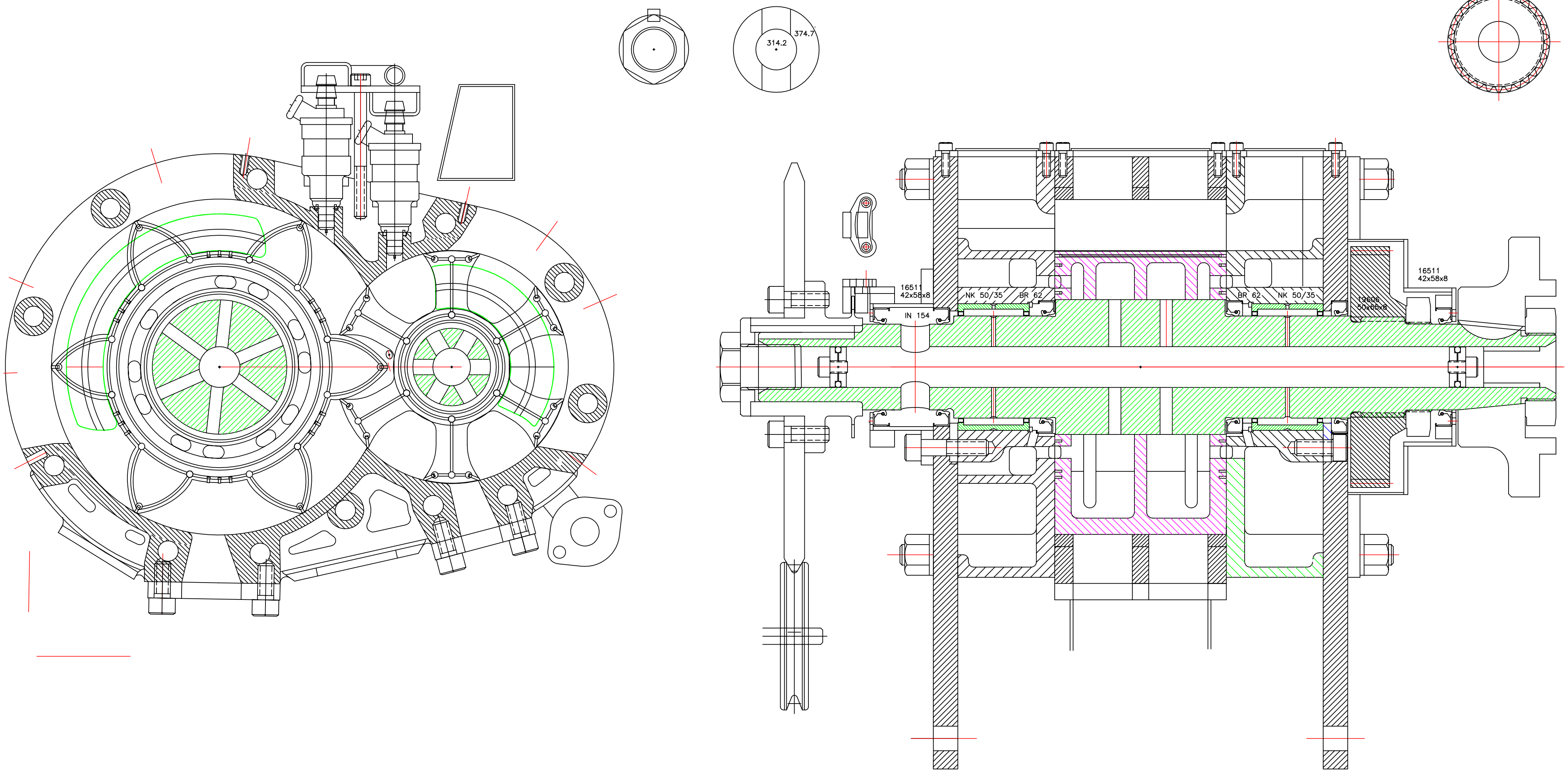
6-28 Test Platform.dwg

D-1



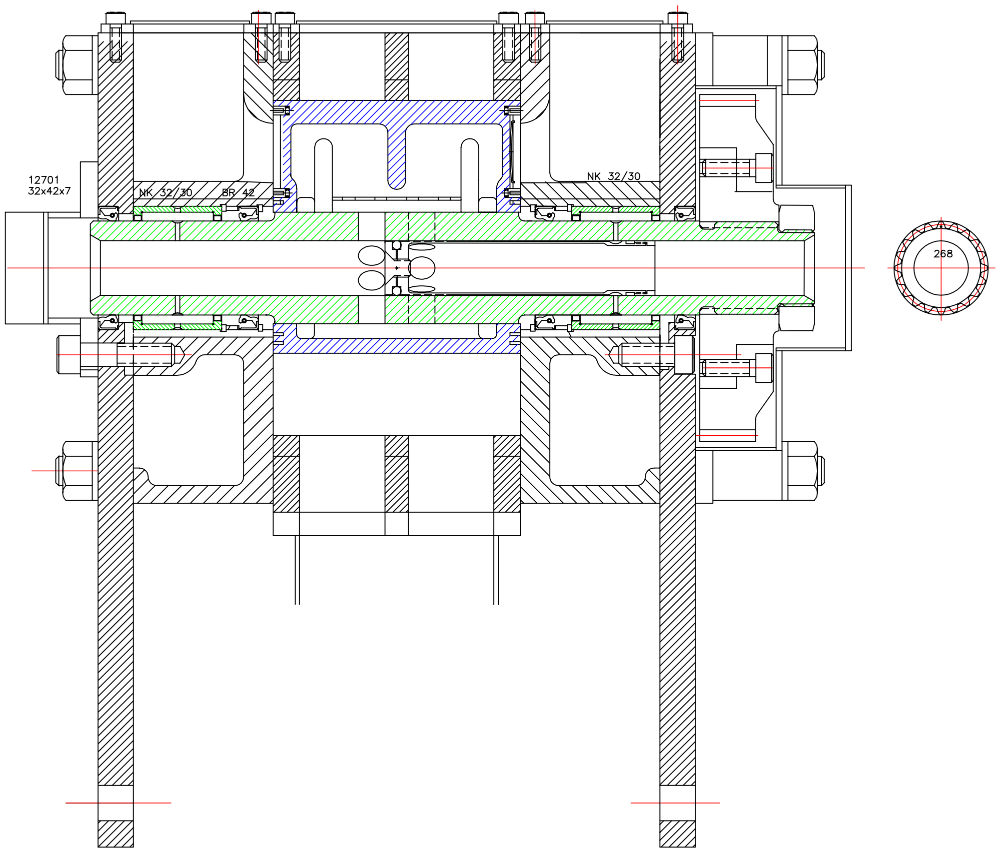
6-1000 Oil Design Layout.dwg

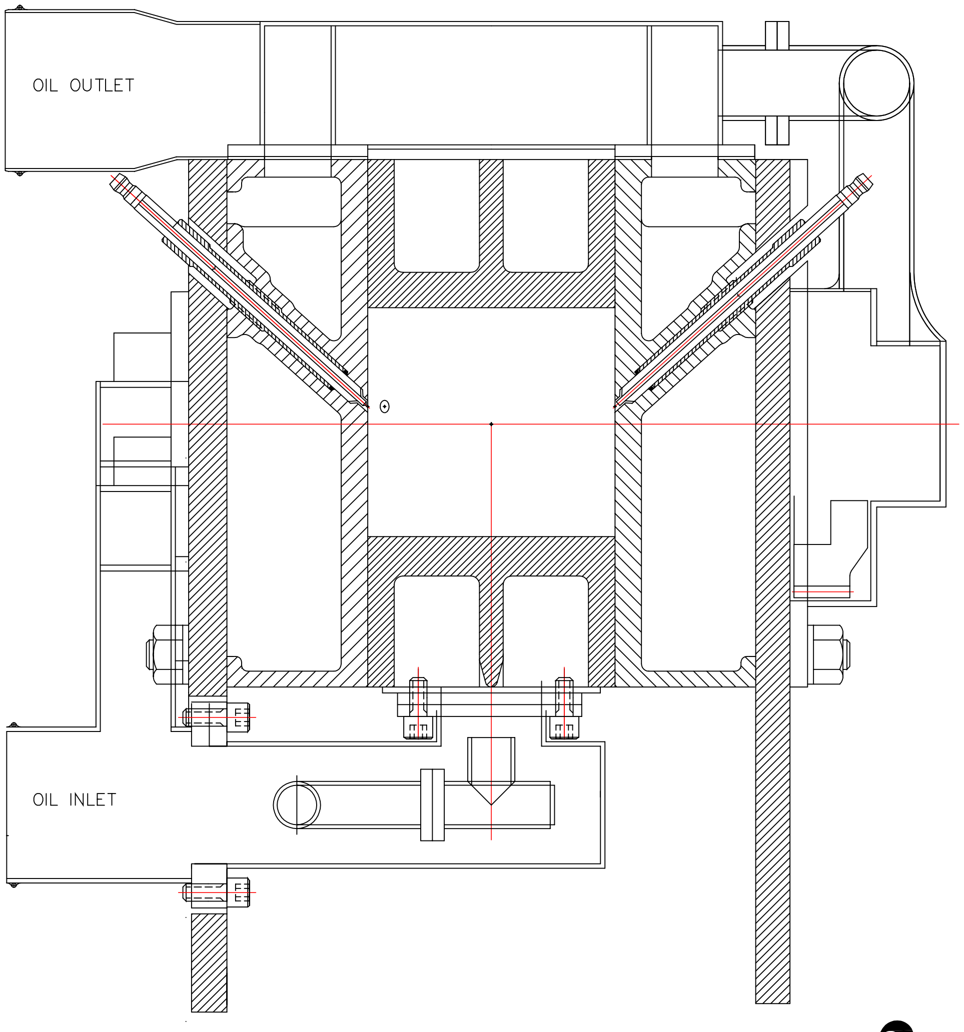
D-2



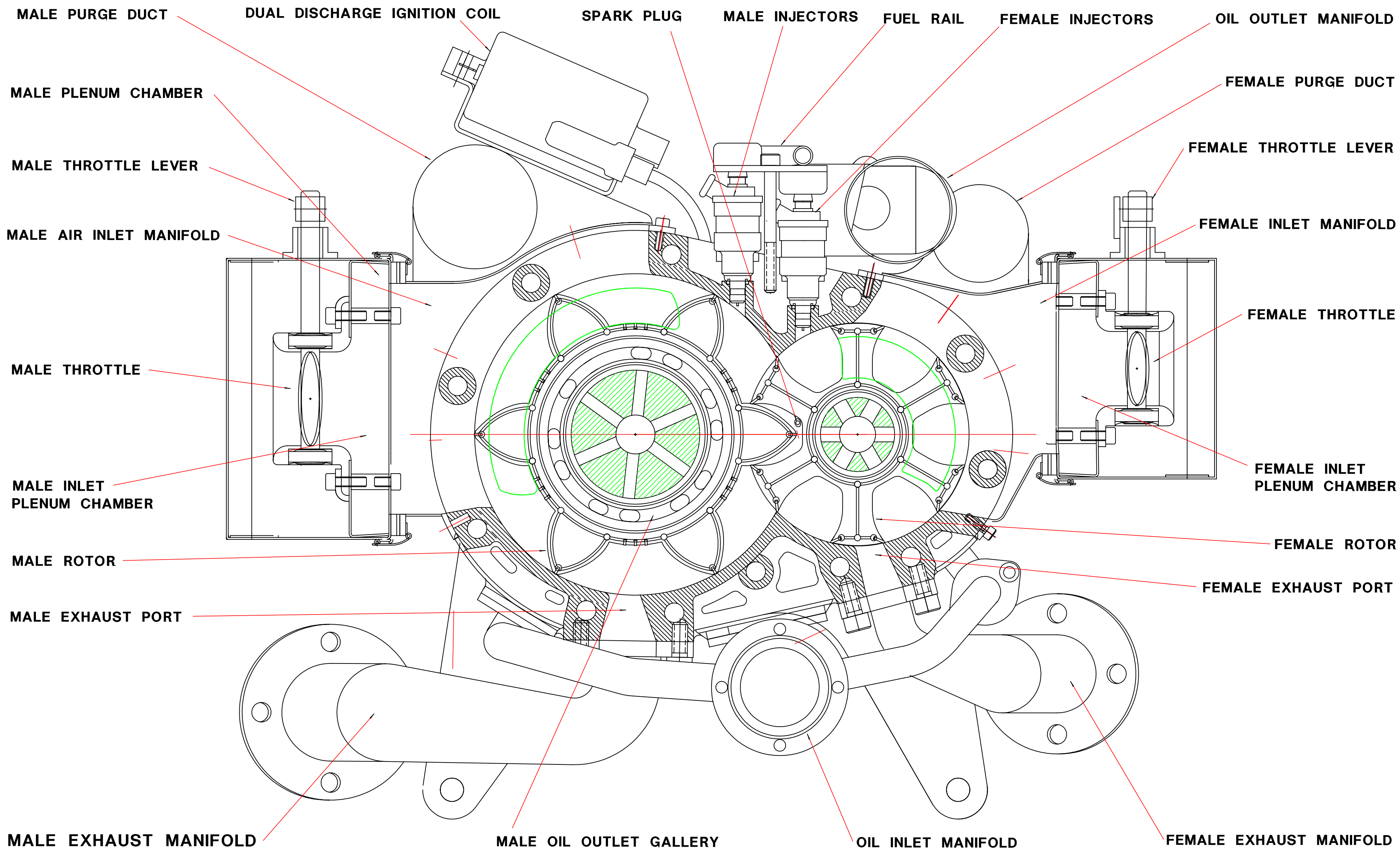
6-1000 Oil **1**

D-3

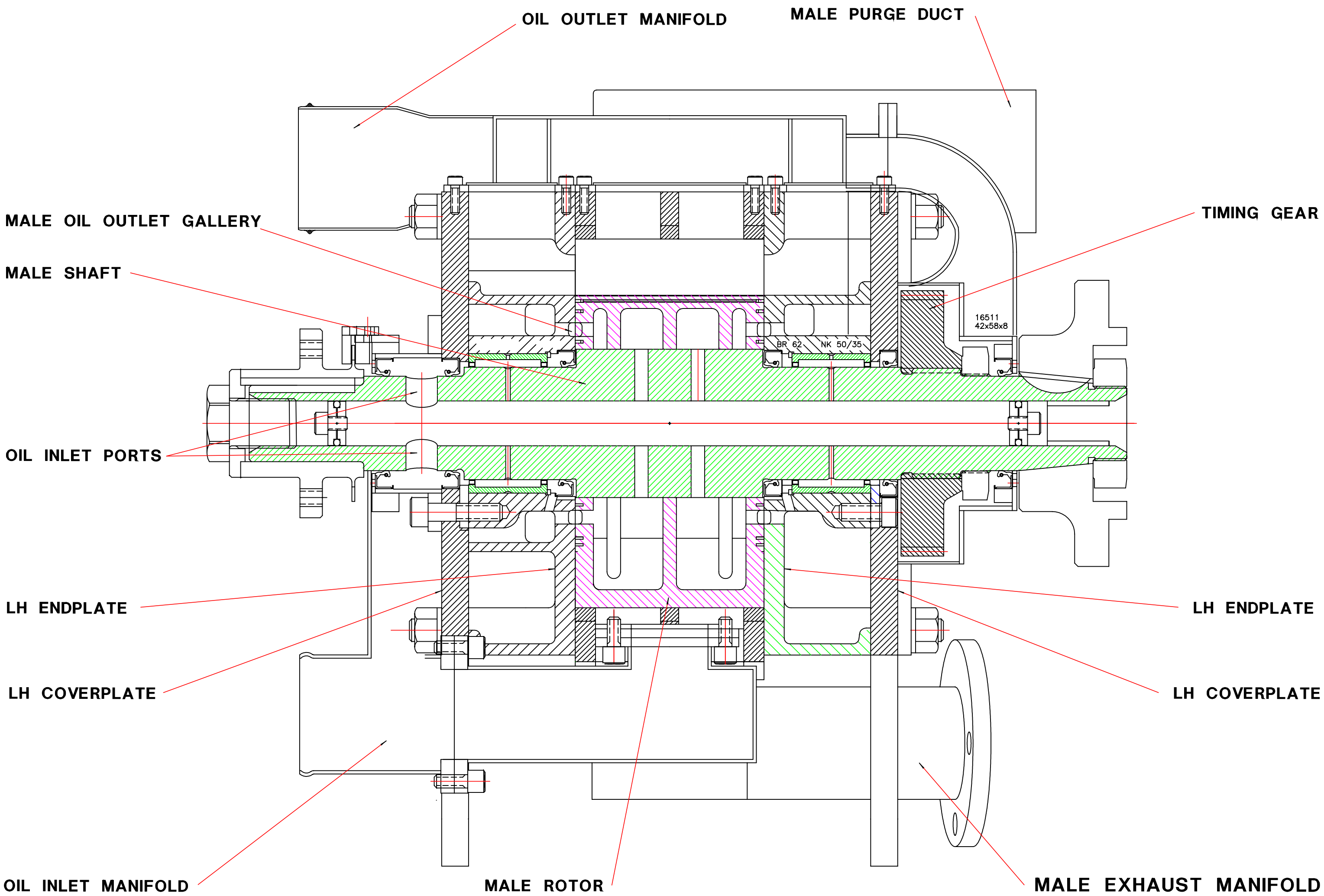


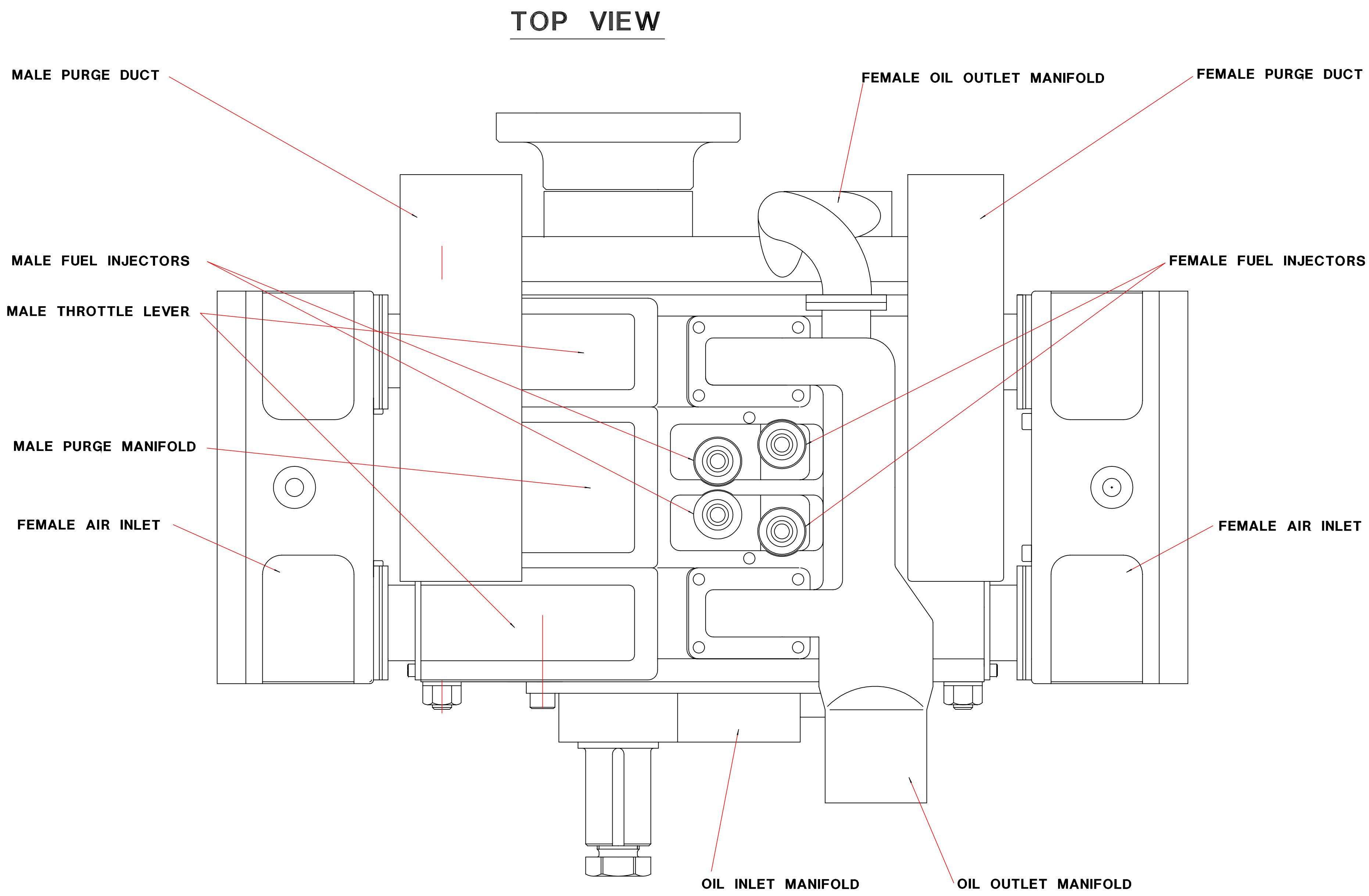


SECTION THROUGH CENTRE LINE

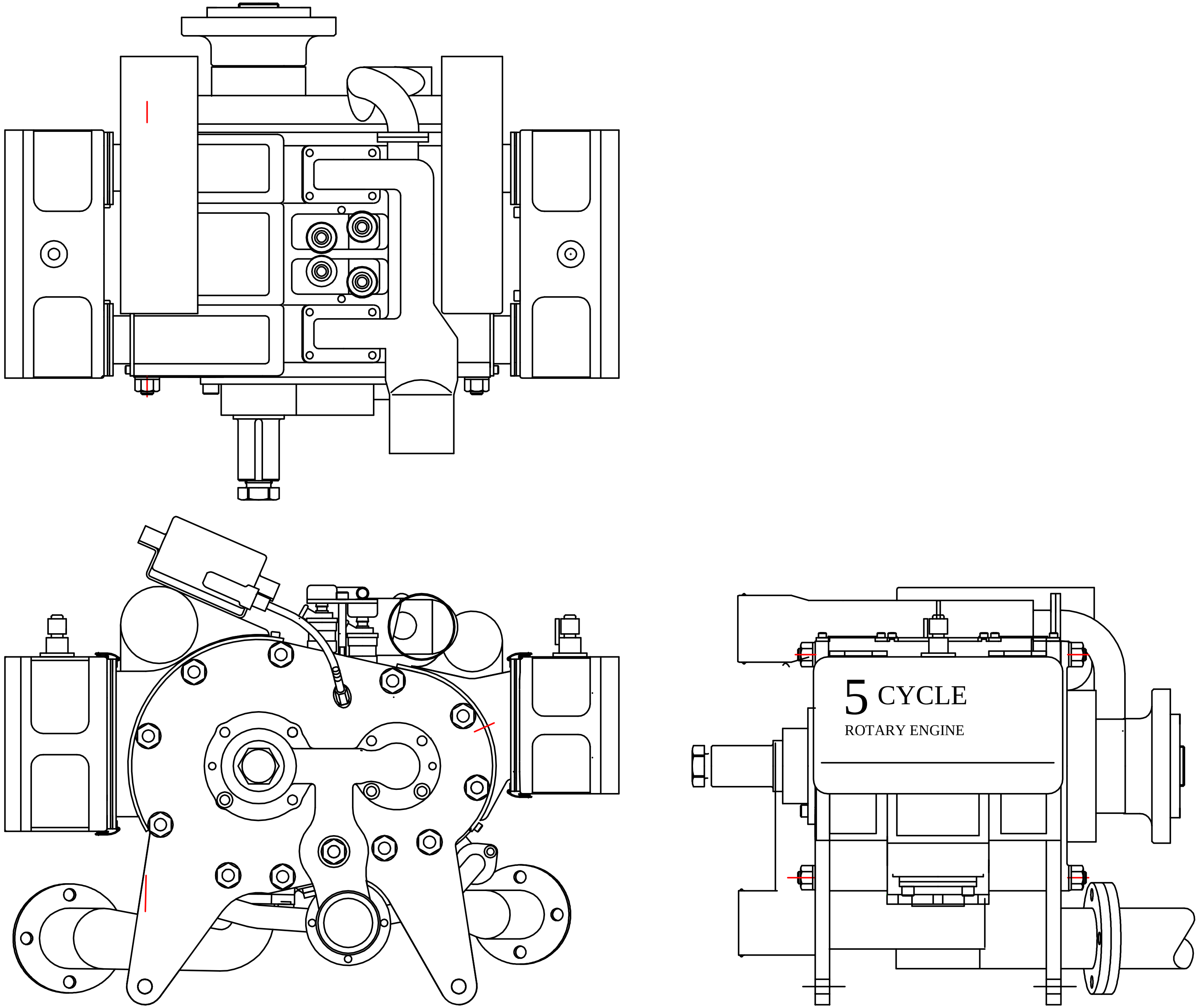


SECTION THROUGH C\L of MALE ROTOR

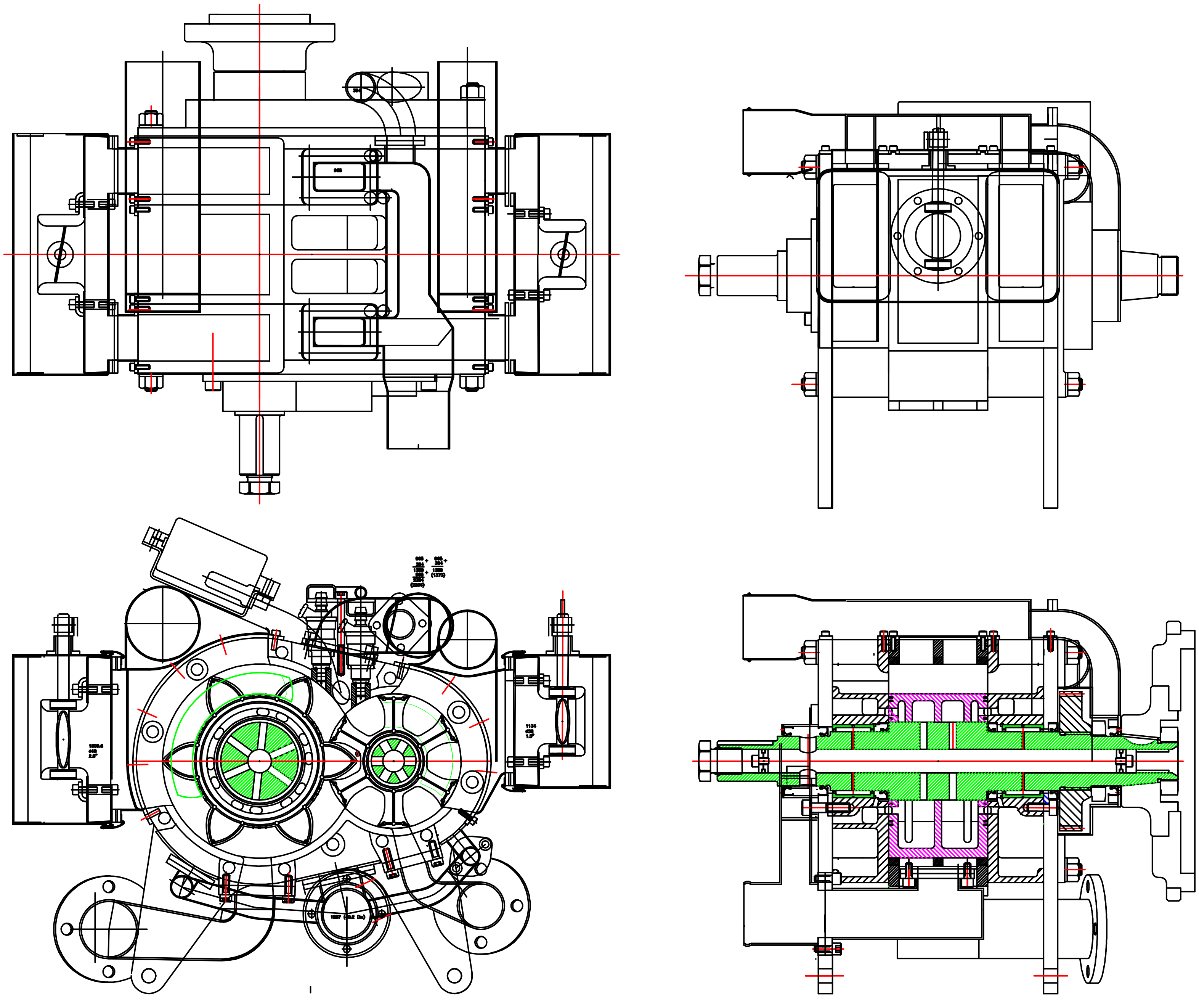



TOP VIEW
MALE PURGE DUCT
FEMALE OIL OUTLET MANIFOLD
FEMALE PURGE DUCT
MALE FUEL INJECTORS
FEMALE FUEL INJECTORS
MALE THROTTLE LEVER
MALE PURGE MANIFOLD
FEMALE AIR INLET
FEMALE AIR INLET
OIL INLET MANIFOLD
OIL OUTLET MANIFOLD

D-7

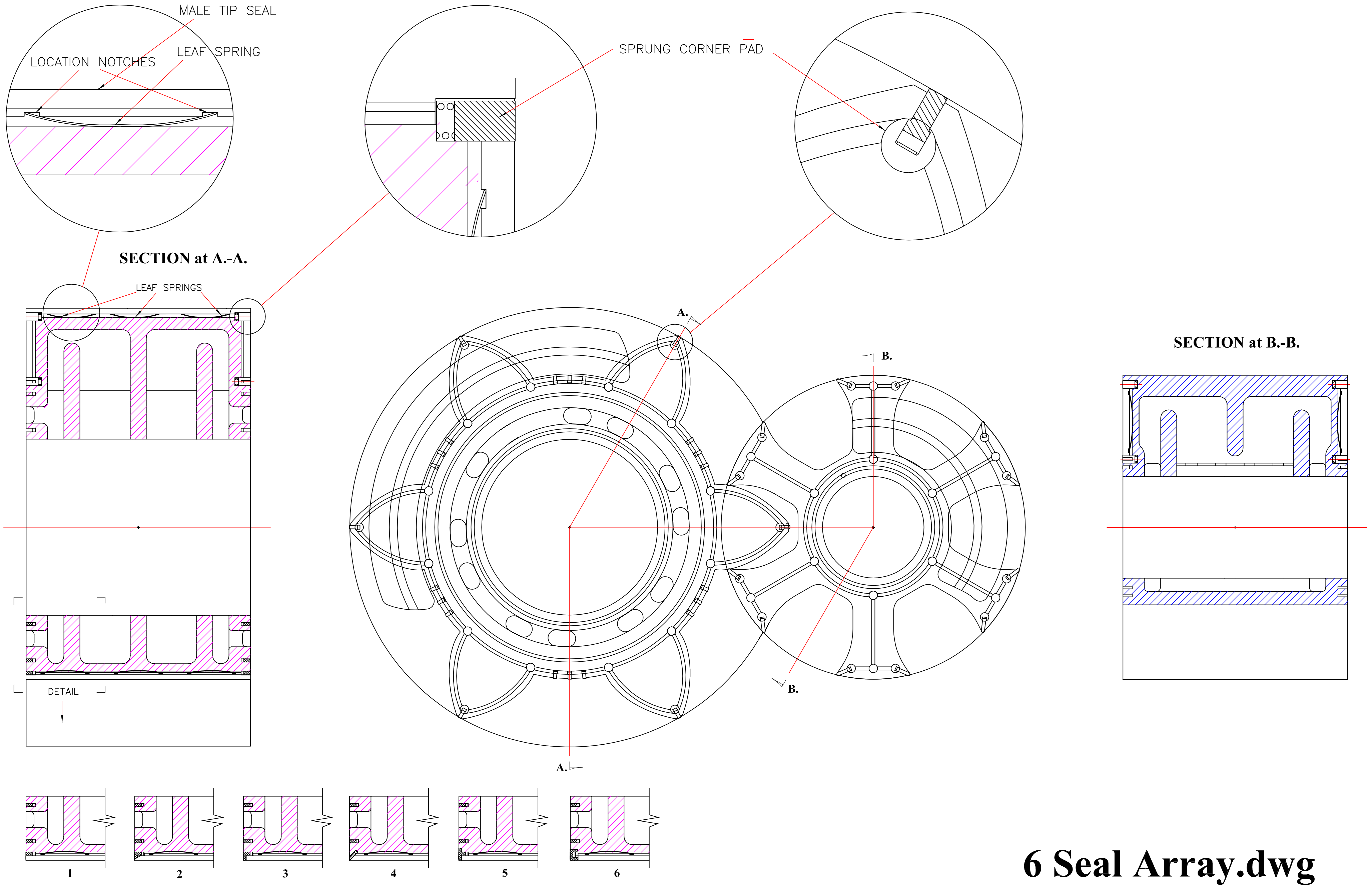


External Views - 1000cc Oil-Cooled 5 Cycle Rotary Engine.



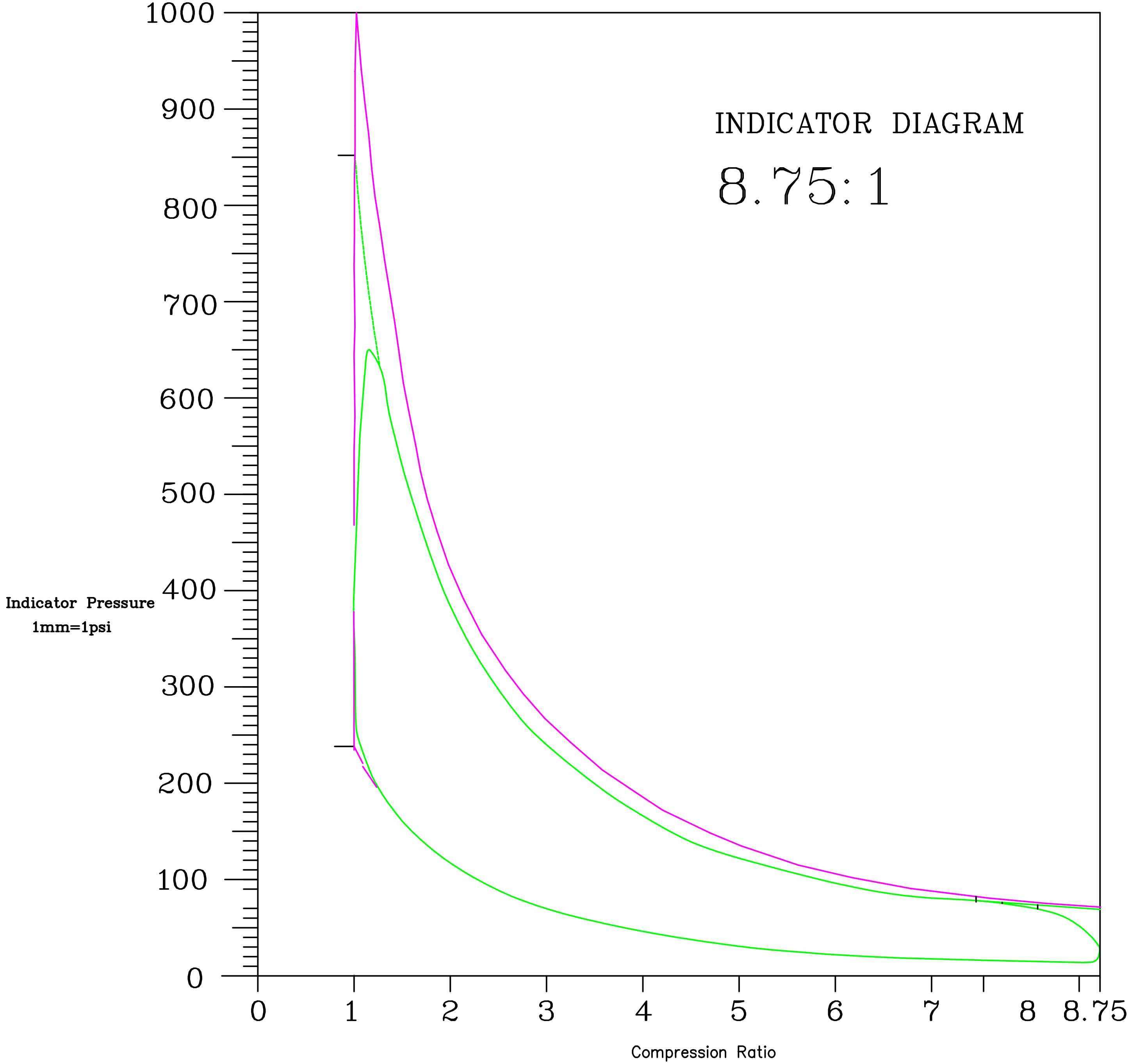
Partial Design Layout of the 1000cc Oil-Cooled 5 Cycle Rotary Engine.

D-9



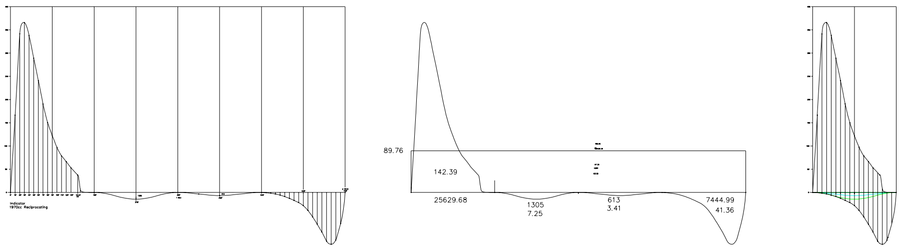
6 Seal Array.dwg

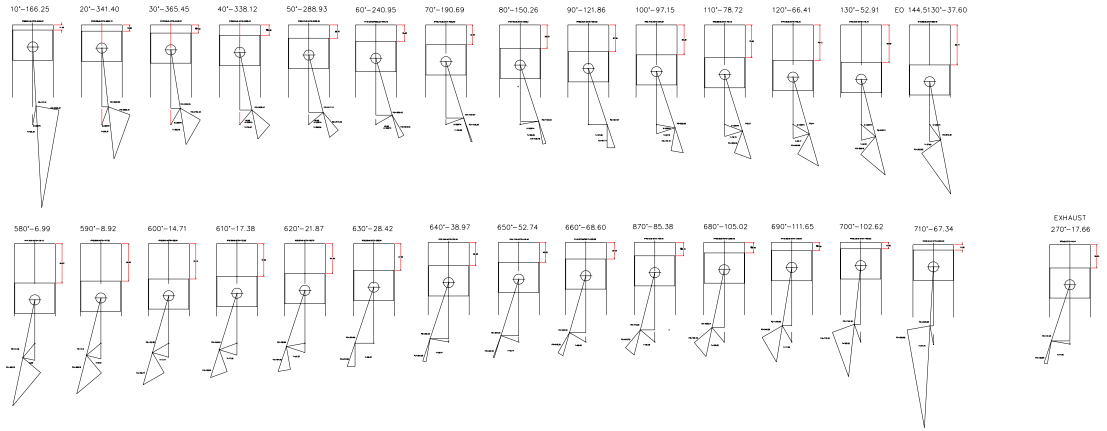
D-10

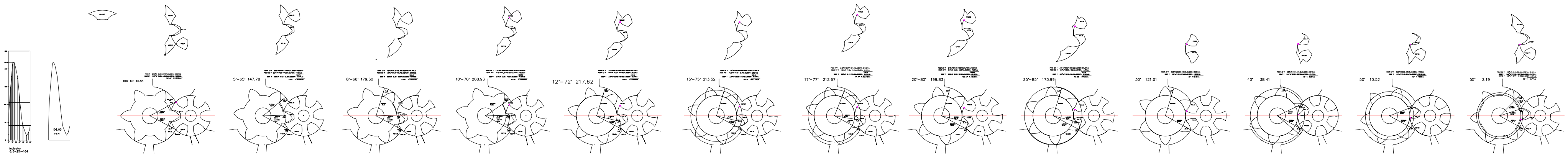


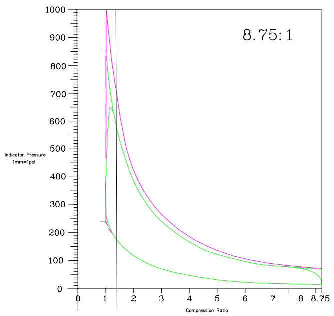
8.75:1 Indicator Diagram.dwg

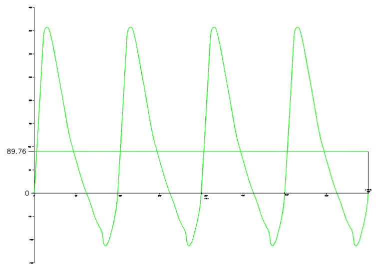
D-11

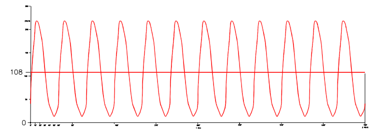


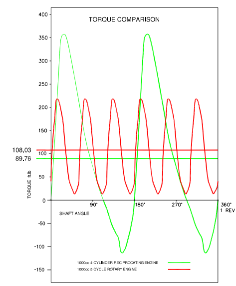




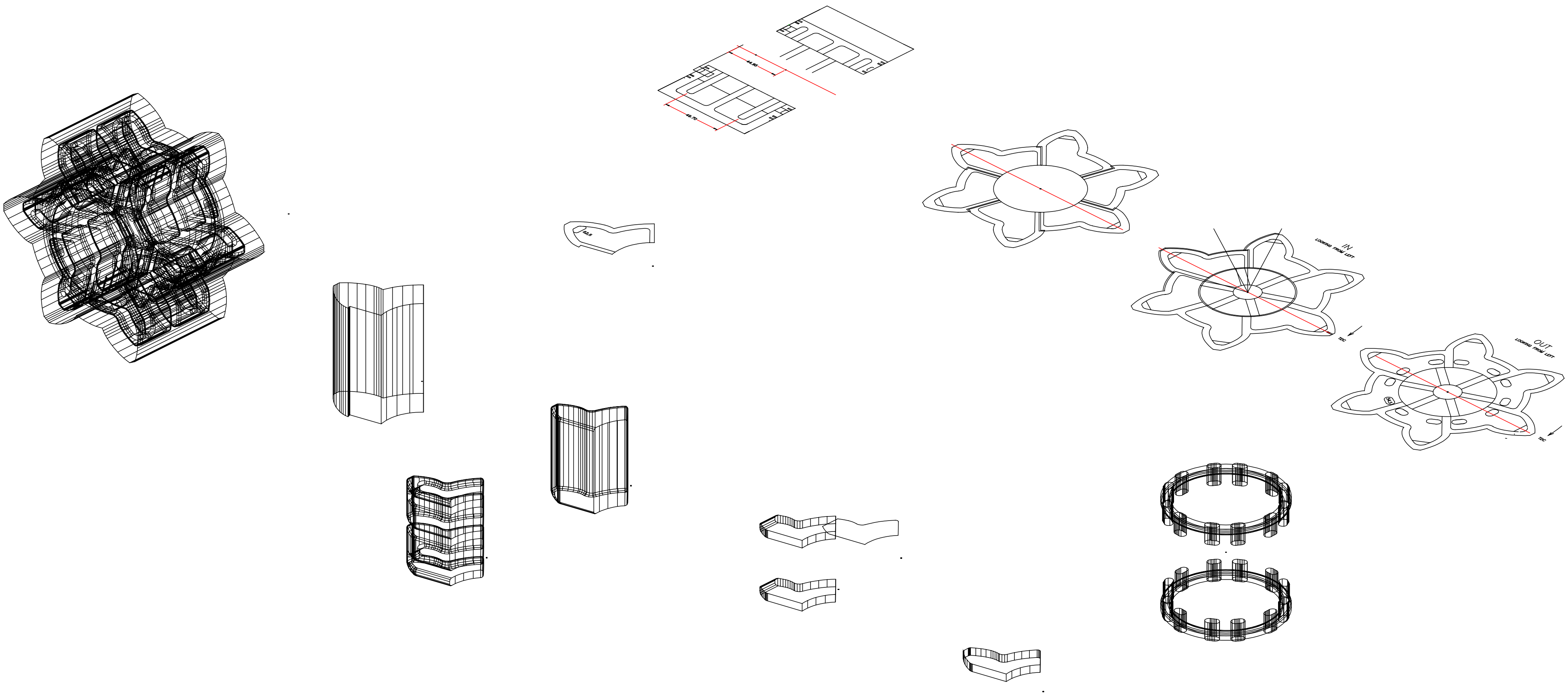




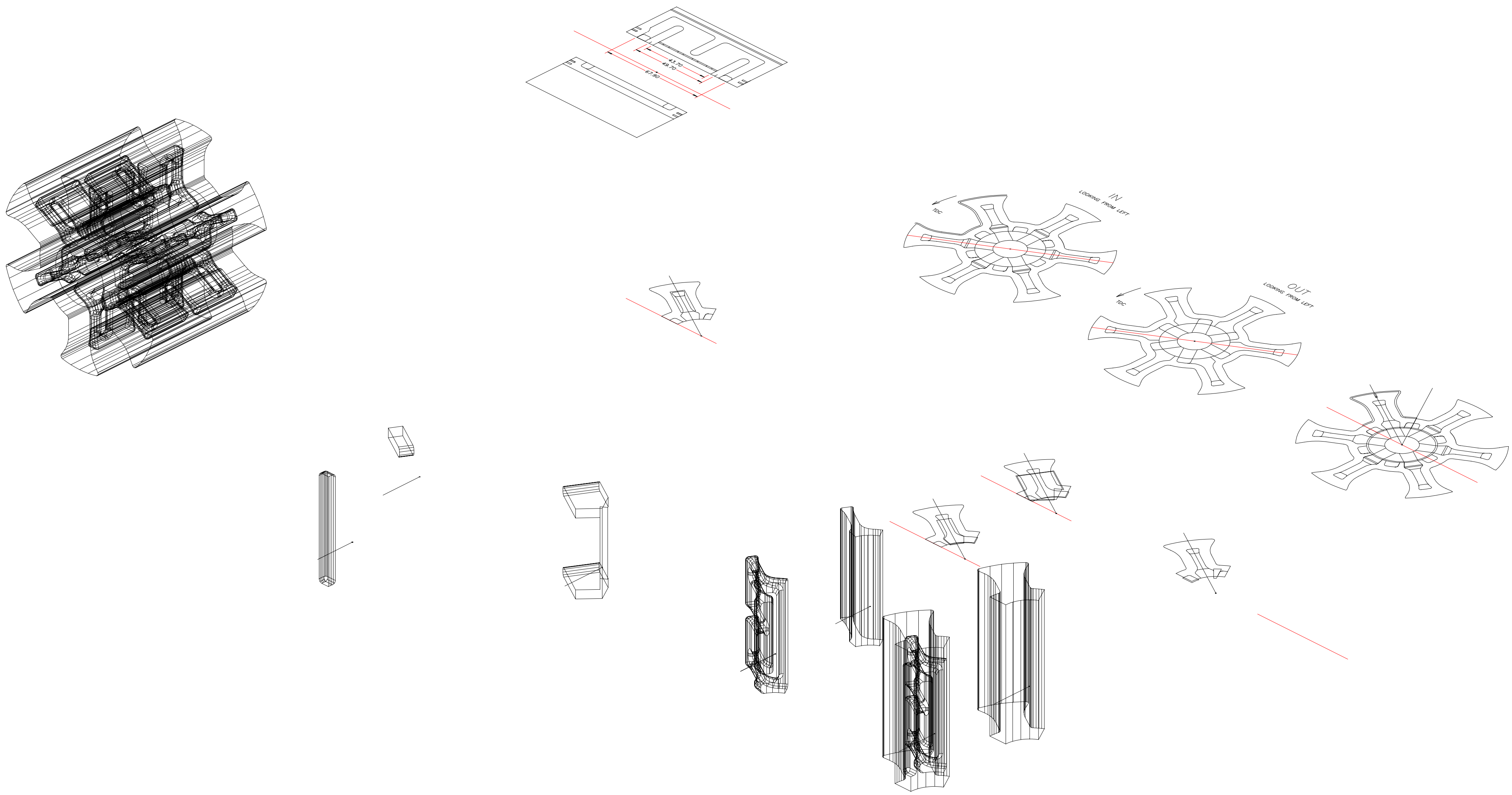




6-1000-Recip Comparison.dwg

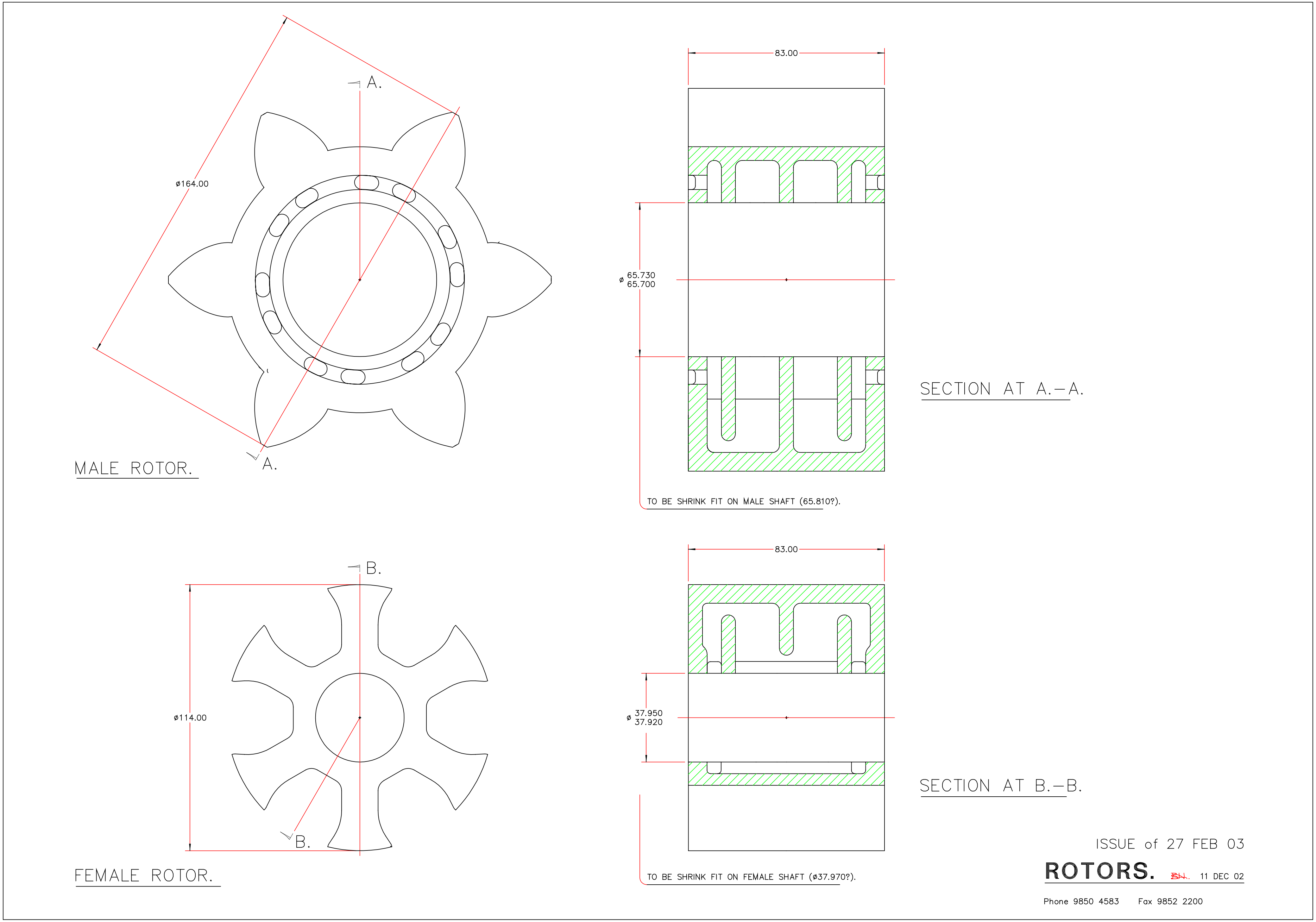


6 Male Rotor Wax.dwg

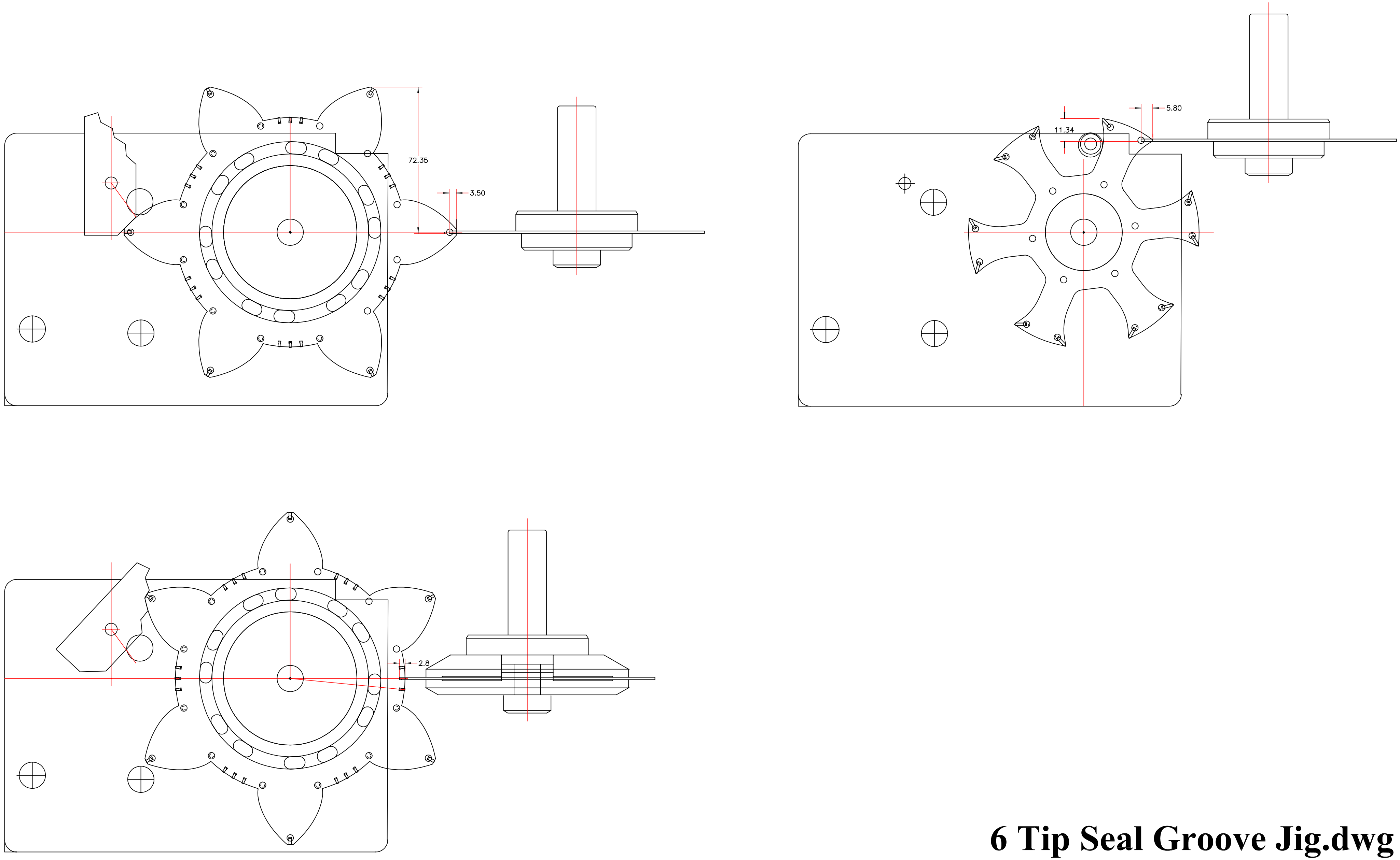


6 Female Rotor Wax.dwg

D-14

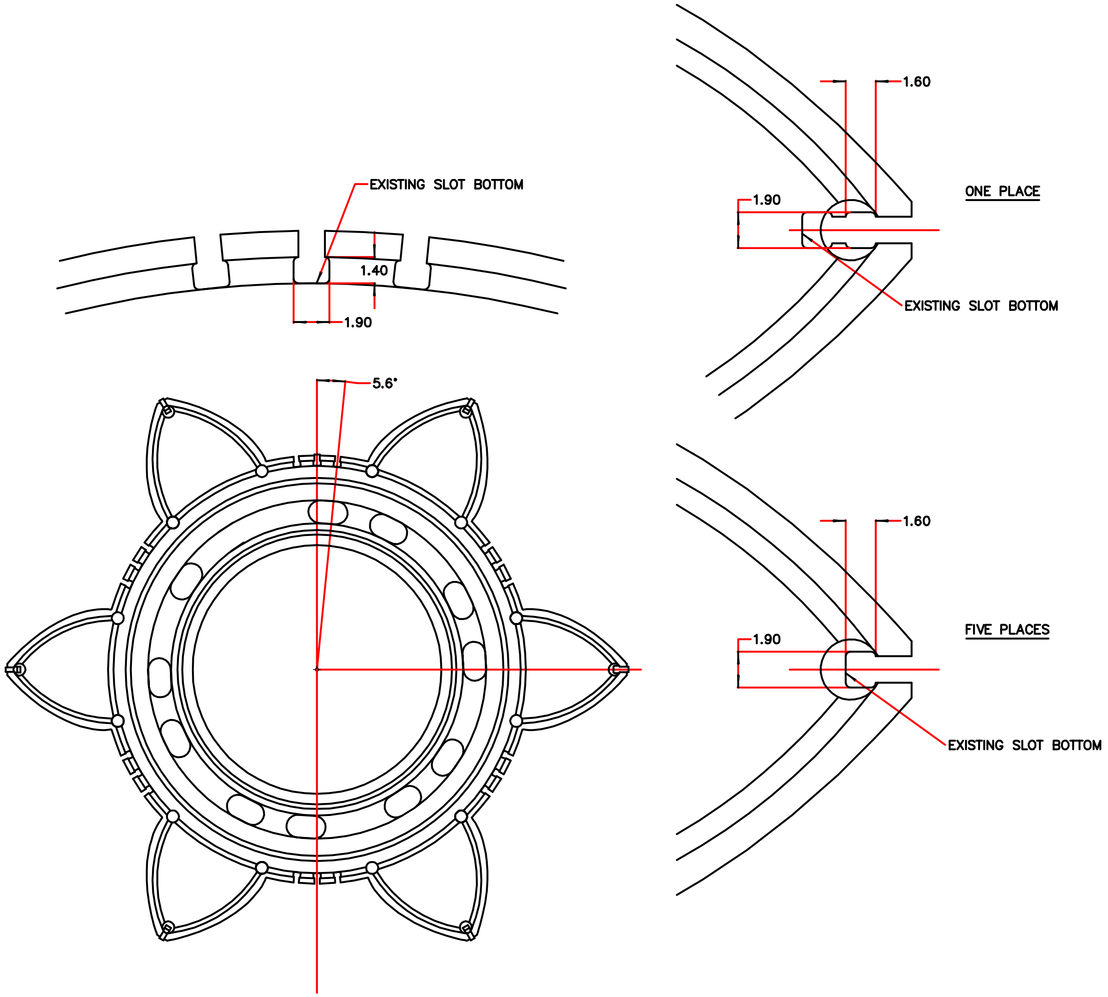


A.
ø164.00
A.
MALE ROTOR.
83.00
ø 65.730
65.700
SECTION AT A.—A.
TO BE SHRINK FIT ON MALE SHAFT (65.810?).
B.
ø114.00
B.
FEMALE ROTOR.
83.00
ø 37.950
37.920
SECTION AT B.—B.
TO BE SHRINK FIT ON FEMALE SHAFT (ø37.970?).
ISSUE of 27 FEB 03
ROTORS.
11 DEC 02
Phone 9850 4583
Fax 9852 2200

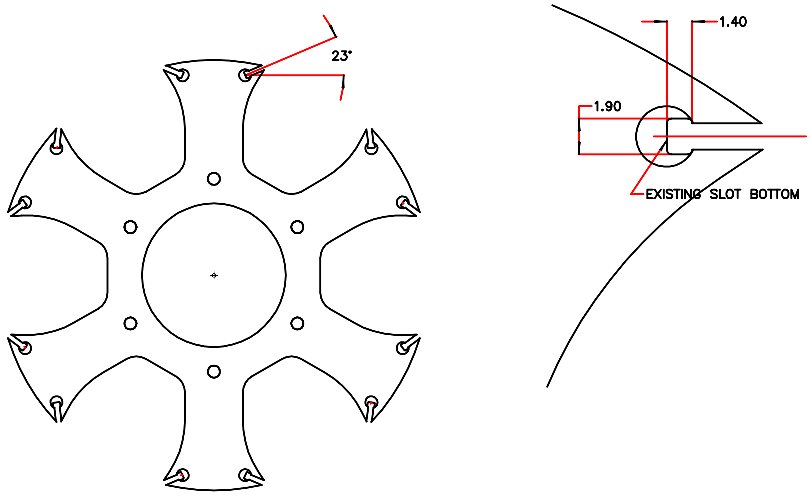


6 Tip Seal Groove Jig.dwg

D-16

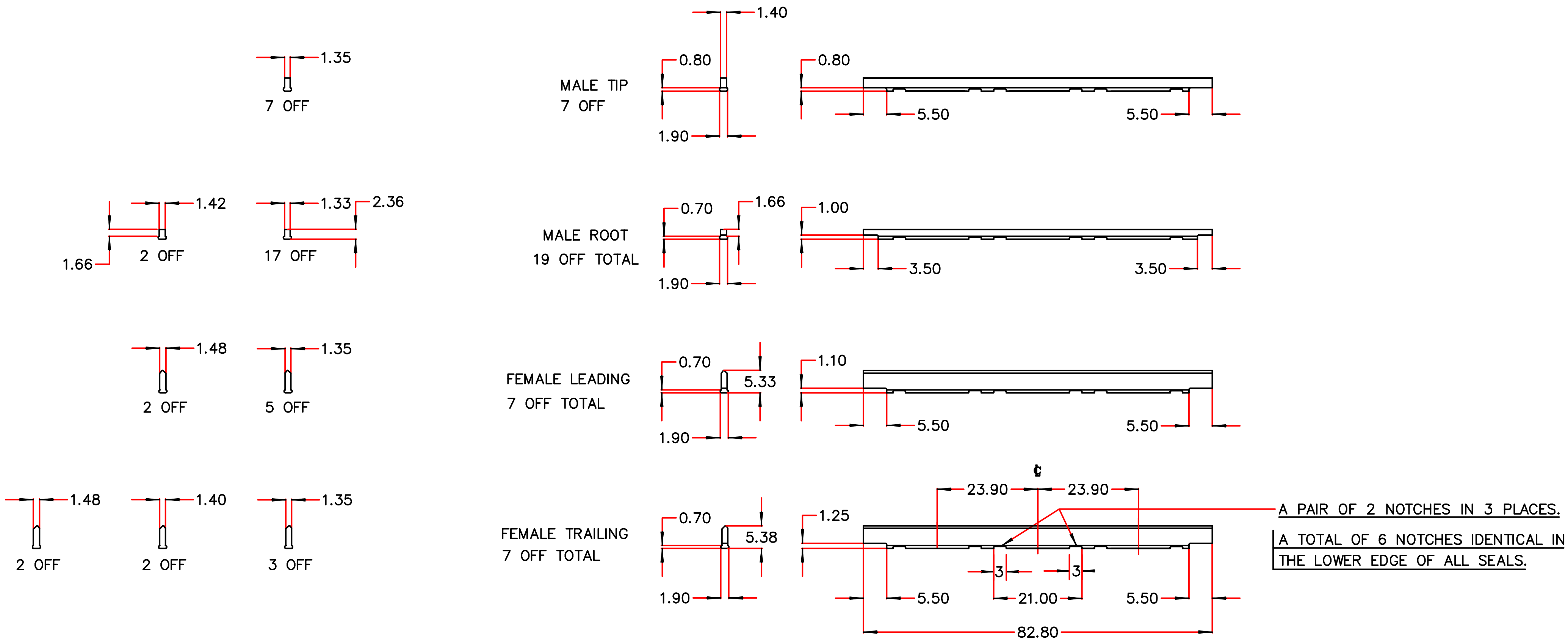


MALE 'TEE' SLOT PROFILES



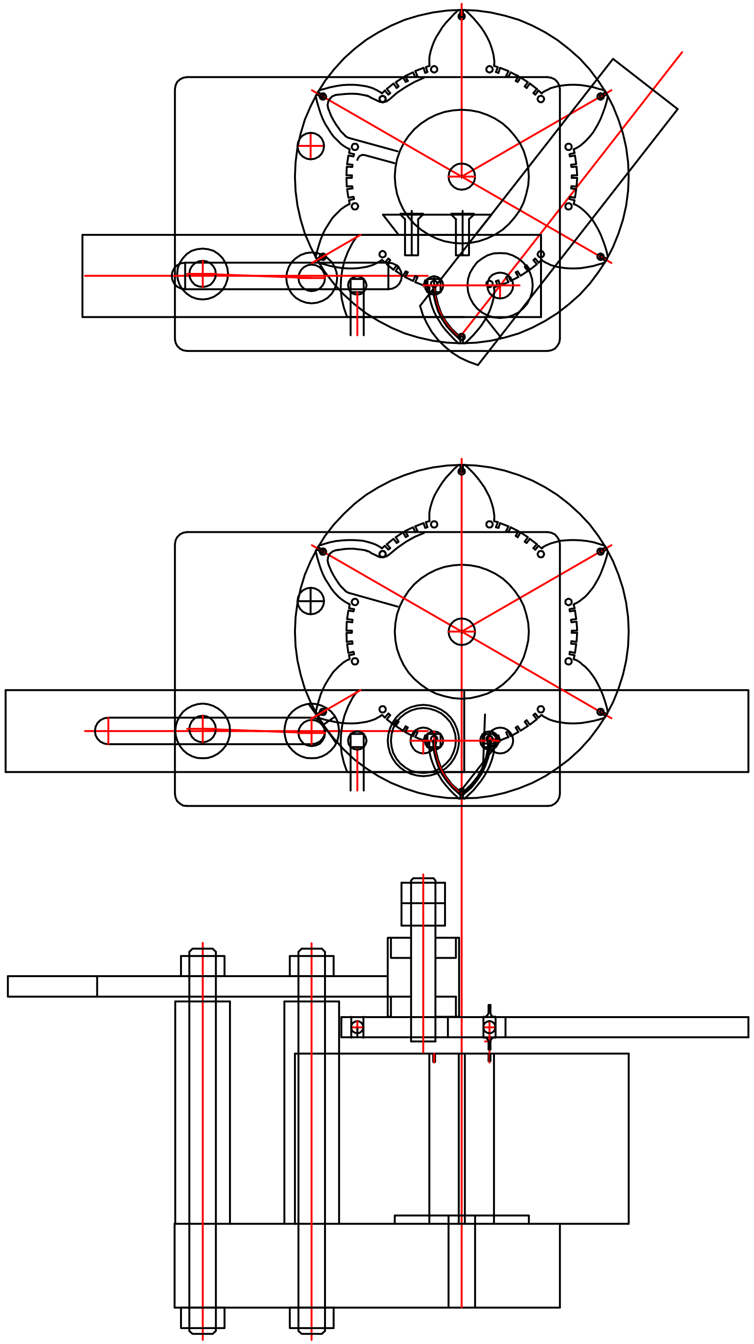
FEMALE 'TEE' SLOT PROFILES

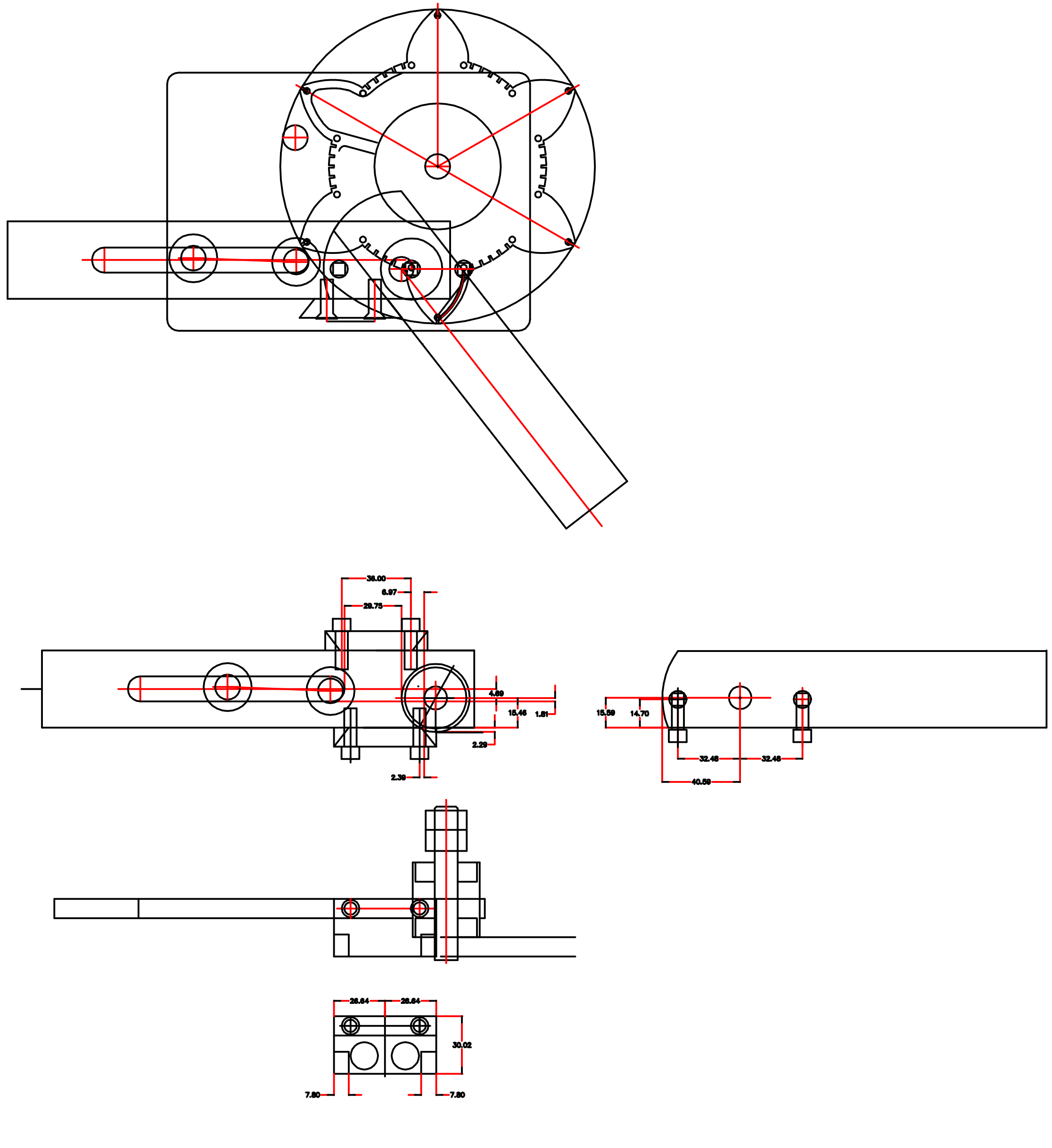
D-17



6 'Tee' Tip Seals.dwg

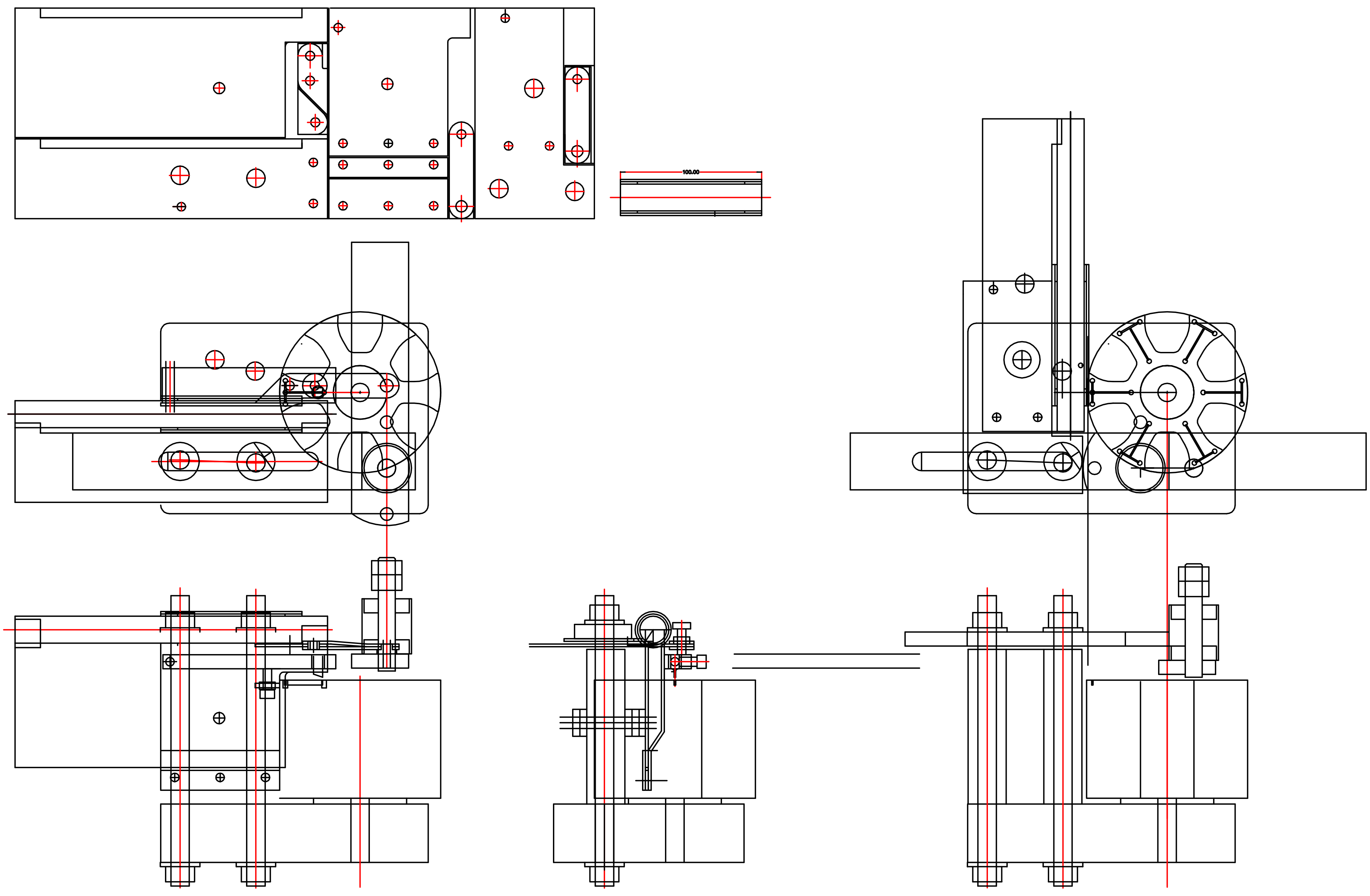
D-18





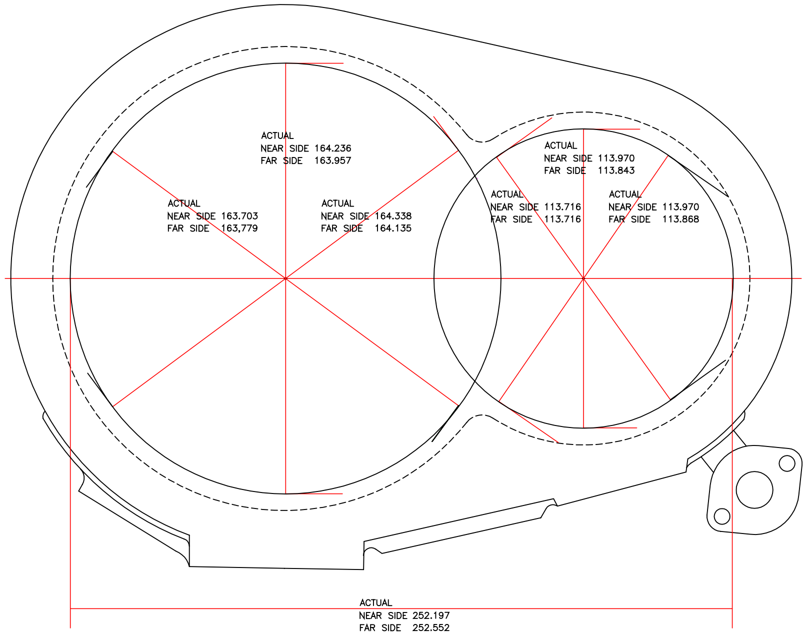
6 Male Rotor End Seal Groove Machine.dwg

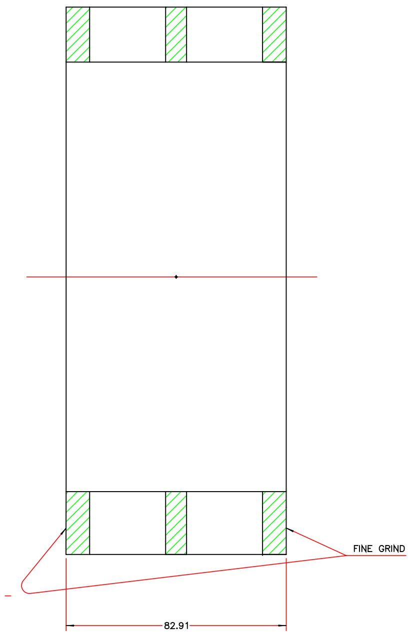
D-19

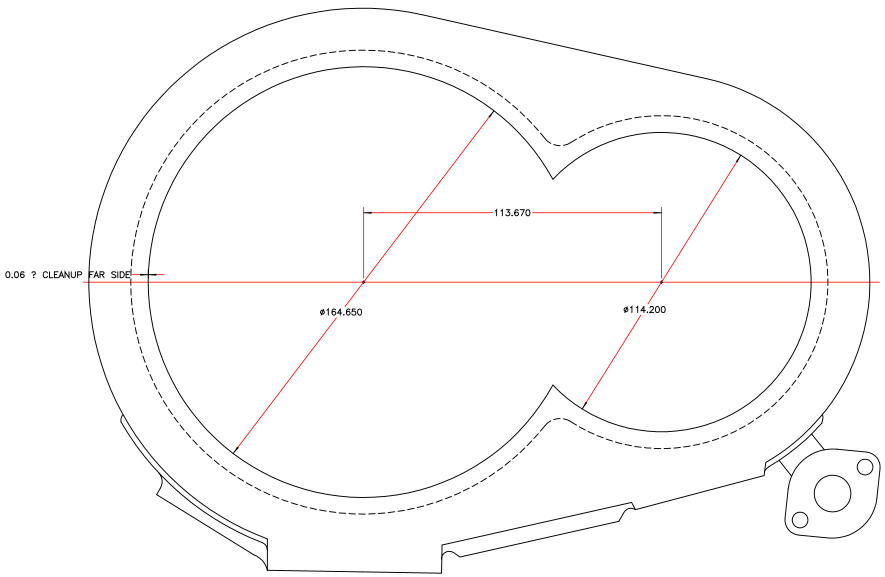


6 Female Rotor End Seal Groove Machine.dwg

D-20



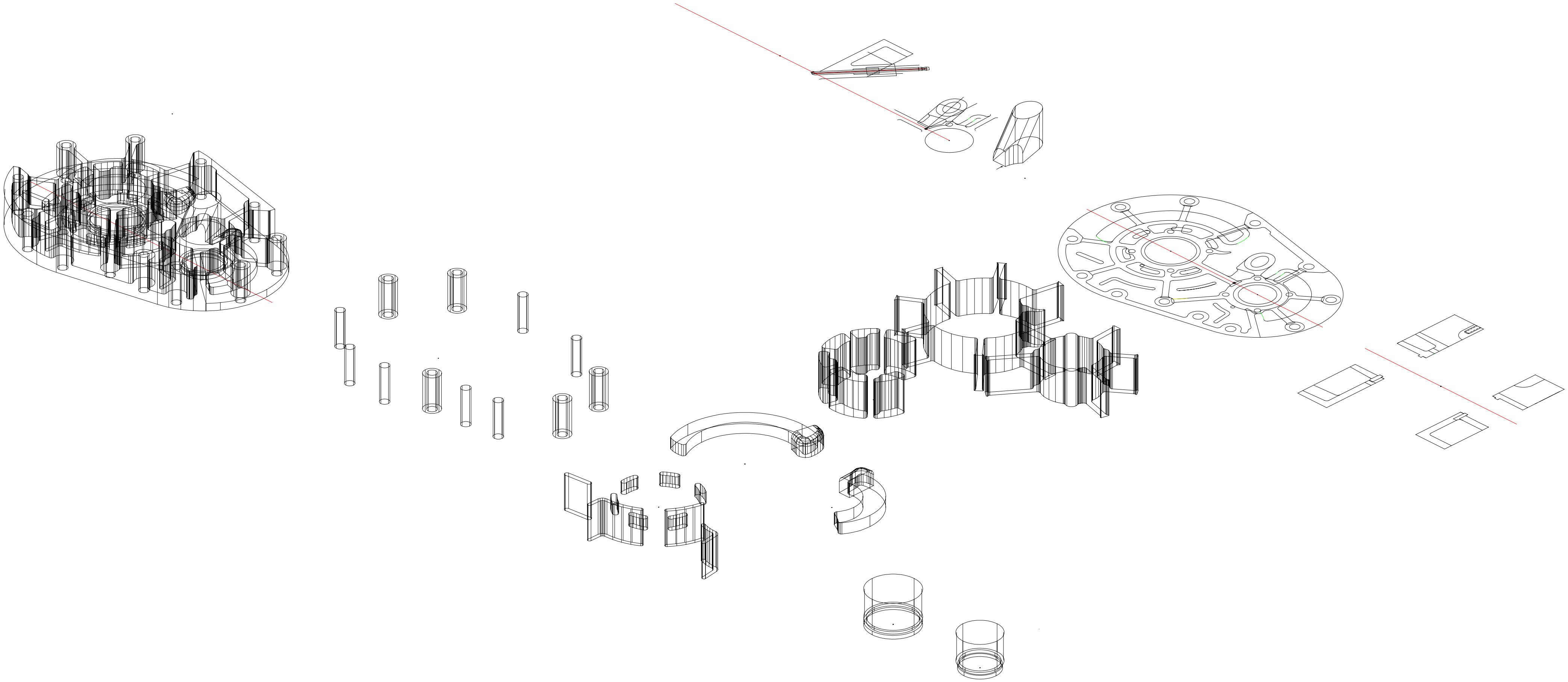




MAIN HOUSING 4 AUG 03

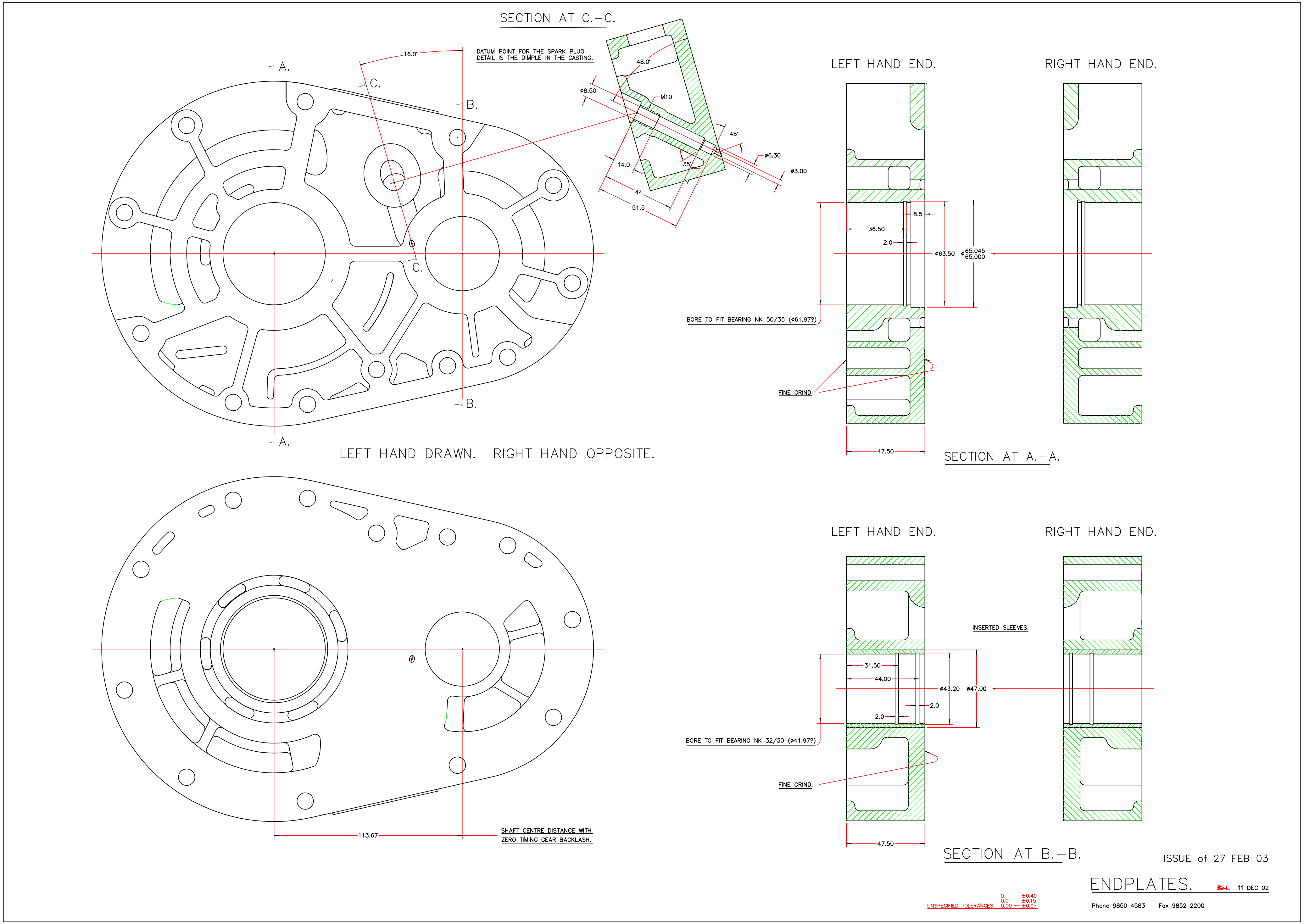
BARRY HUDSON
60 Chatsworth Quadrant
Lower Templestowe 3107
Phone 9850 4583 Fax 9852 2200
Emial bhid@smartchat.net.au

D-21

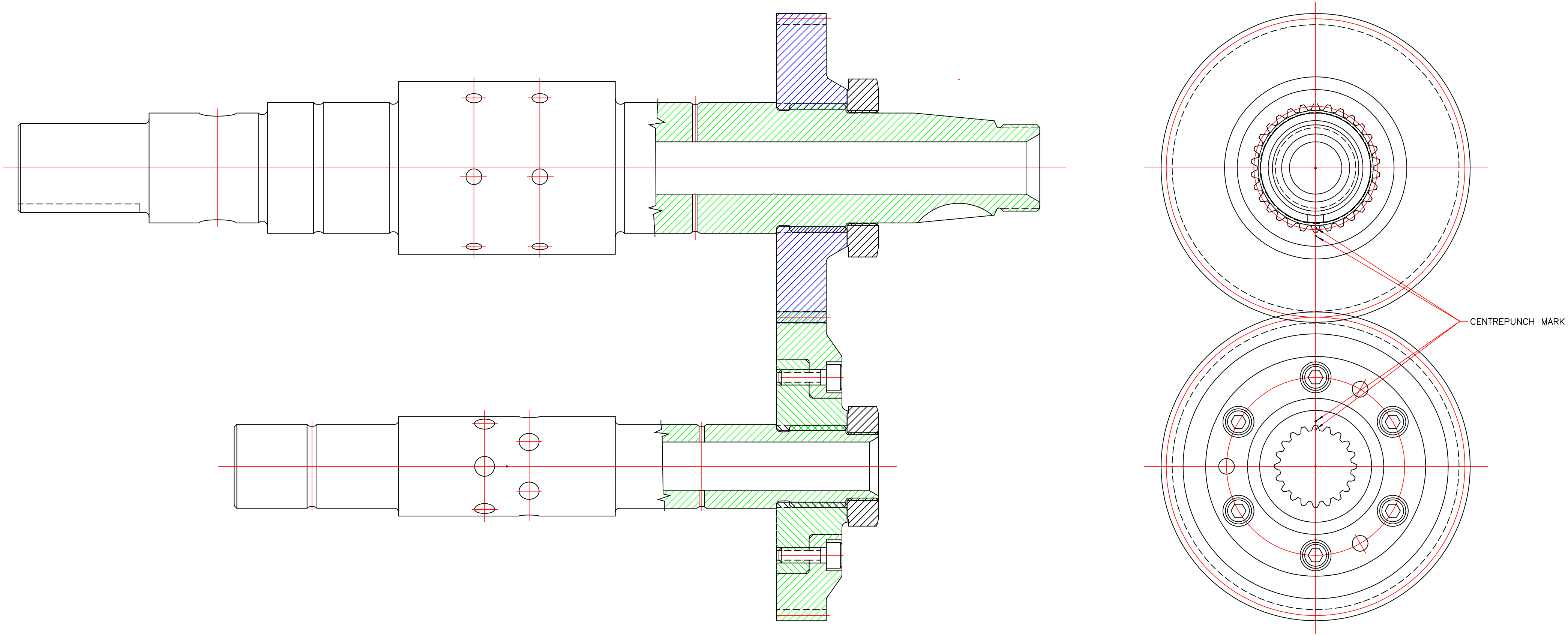


6 LH End.dwg

D-22



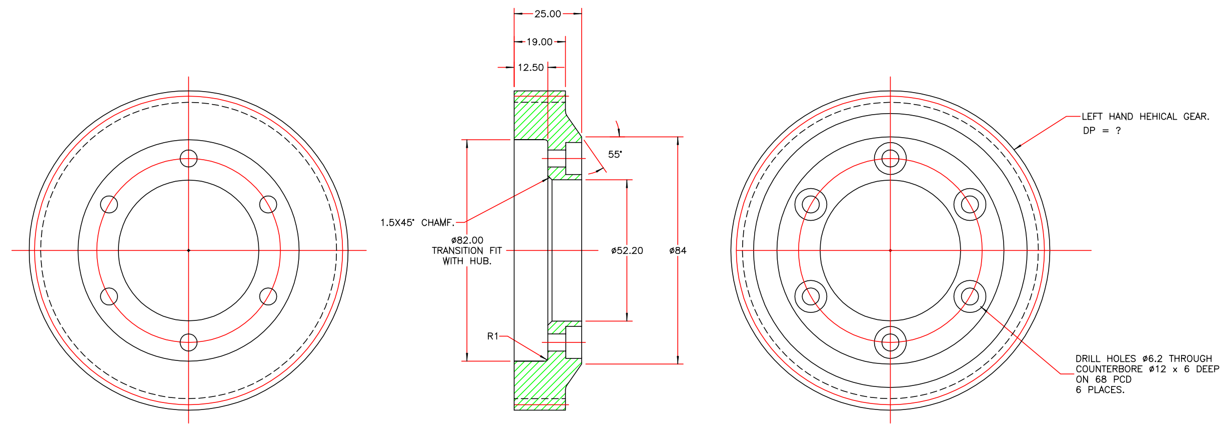
SECTION AT C.–C.
DATUM POINT FOR THE SPARK PLUG
DETAIL IS THE DIMPLE IN THE CASTING.
16.0°
48.0°
ø8.50
M10
45°
ø6.30
ø3.00
14.0
35°
44
51.5
A.
B.
C.
LEFT HAND DRAWN. RIGHT HAND OPPOSITE.
LEFT HAND END.
RIGHT HAND END.
8.5
36.50
2.0
ø63.50
ø65.045
65.000
BORE TO FIT BEARING NK 50/35 (ø61.97?)
FINE GRIND.
47.50
SECTION AT A.–A.
INSERTED SLEEVES.
31.50
44.00
ø43.20
ø47.00
2.0
BORE TO FIT BEARING NK 32/30 (ø41.97?)
113.67
SHAFT CENTRE DISTANCE WITH
ZERO TIMING GEAR BACKLASH.
SECTION AT B.–B.
ISSUE of 27 FEB 03
ENDPLATES.
11 DEC 02
UNSPECIFIED TOLERANCES. 0 ±0.40 0.0 ±0.15 0.00 ±0.07
Phone 9850 4583 Fax 9852 2200



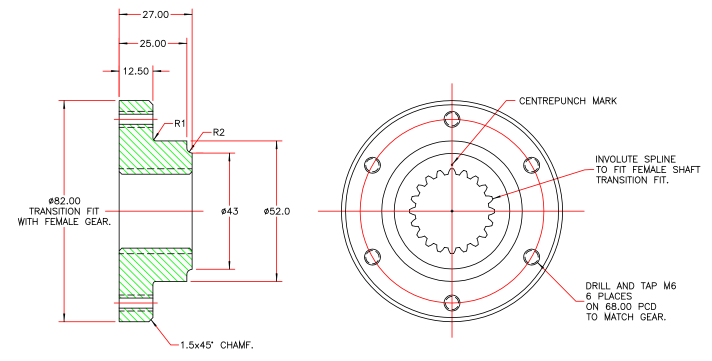
6 Gears-Shafts Assembly.dwg

D-24

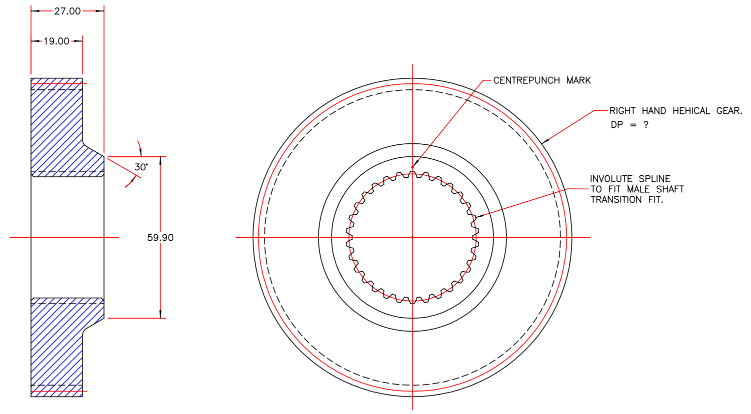
FEMALE GEAR.



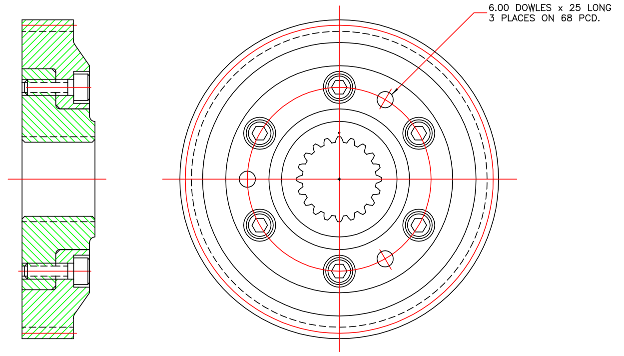
FEMALE GEAR HUB.



MALE GEAR.



FEMALE GEAR ASSEMBLY.



CENTRE DISTANCE BETWEEN MALE AND FEMALE SHAFTS IS 114.00.

RATIO = 1:1.

16 DP

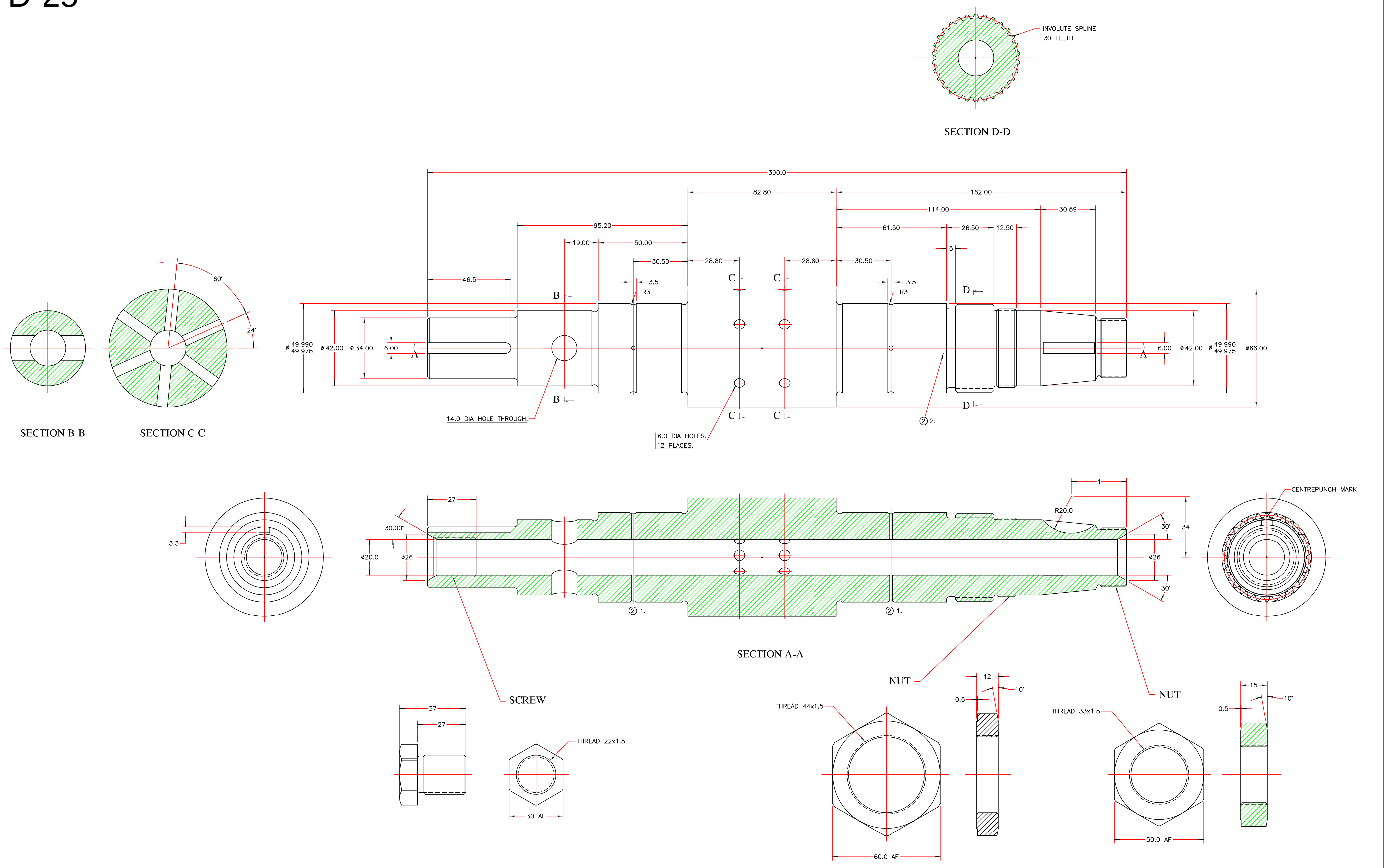
60 TEETH

MATERIALS ?

UNSPECIFIED TOLERANCES.	0	±0.40
	0.0	±0.15
	0.00	±0.07

BHID	FOR	DATE 24 AUG 01	SCALE FULL	PART MALE & FEMALE GEARS
		DRAWN BH		

D-25



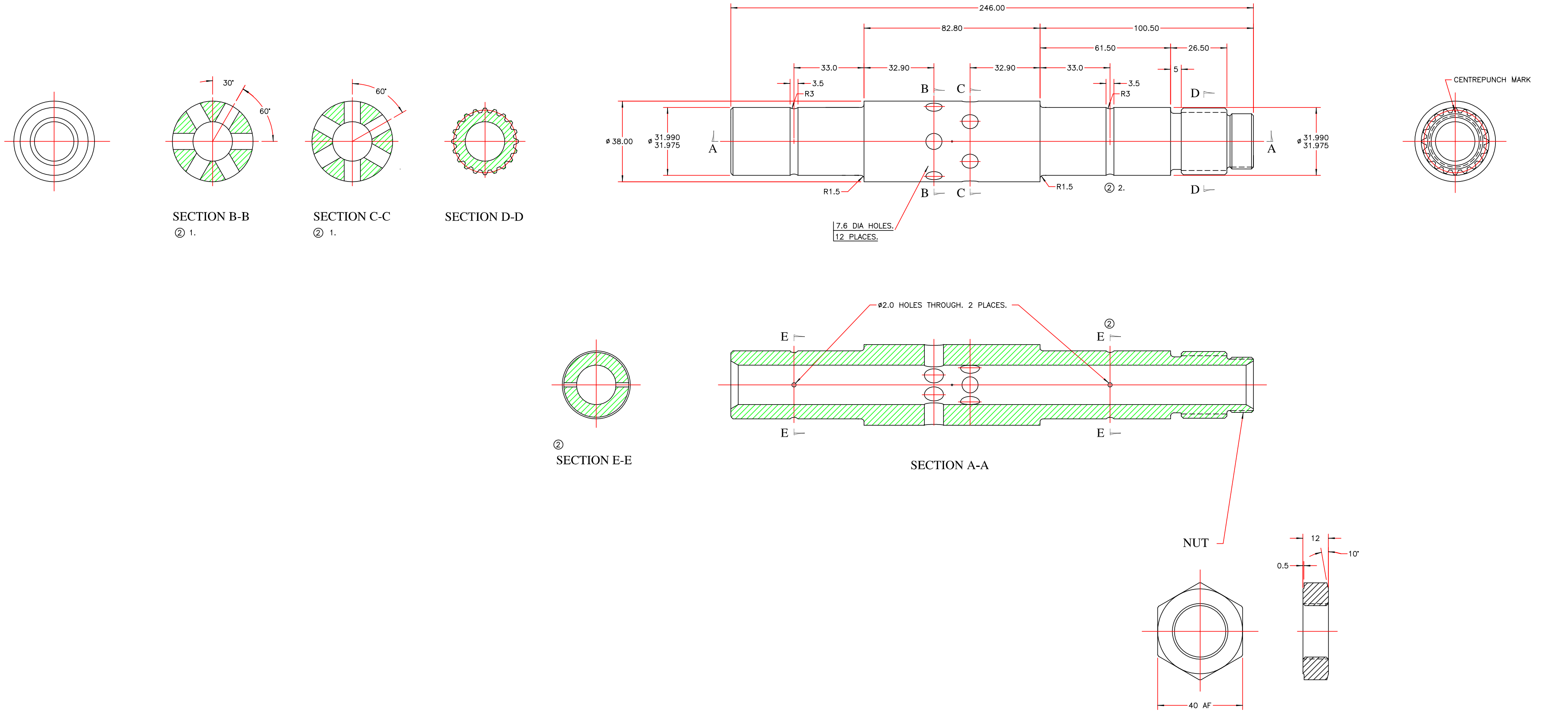
ISSUE ② 16 SEPT 01
1. OIL HOLES ARE NOW THROUGH BOTH SIDES.
2. OIL HOLE DELETED.

3RD ANGLE PROJECTION

UNSPECIFIED TOLERANCES. 0 ±0.40, 0.0 ±0.15, 0.00 — ±0.07

BHID	FOR	DATE 24 AUG 01 / DRAWN	SCALE FULL	PART MALE SHAFT

D-26

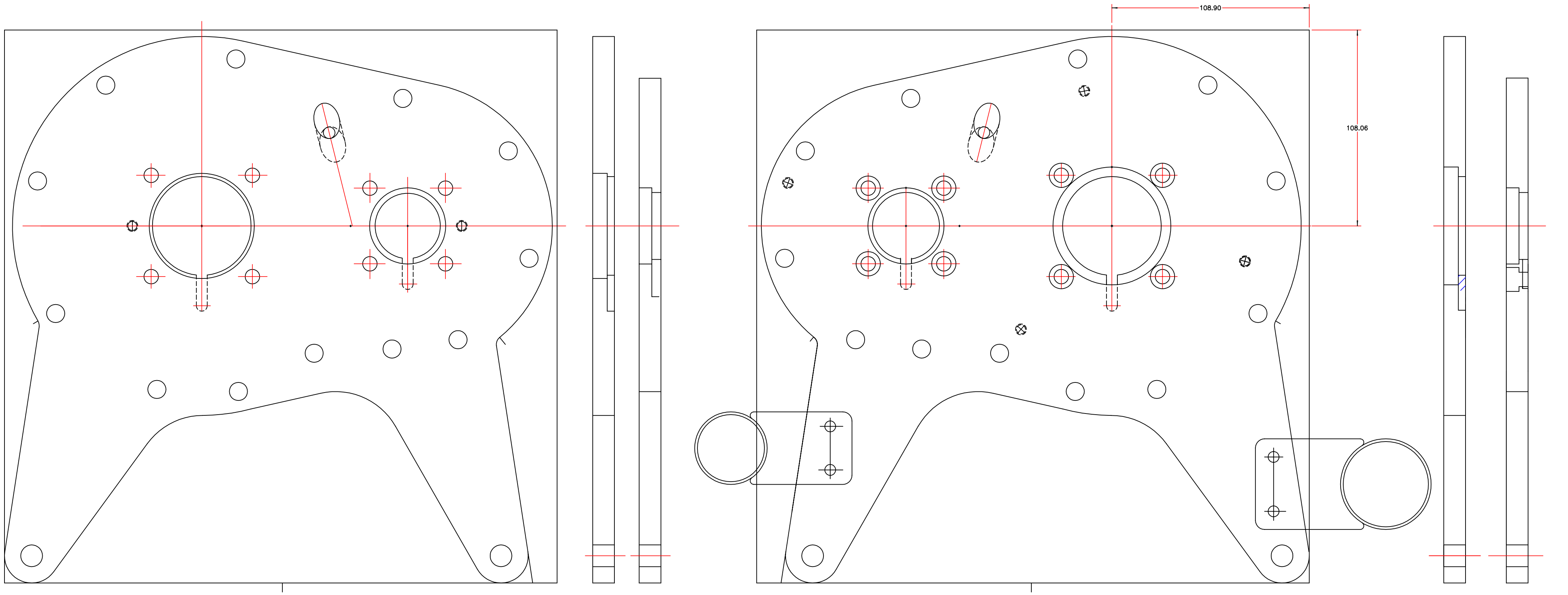


ISSUE ② 16 SEPT 01 1. COOLING HOLES ORIENTATION CHANGED.
2. OIL GROOVE AND HOLES ADDED.

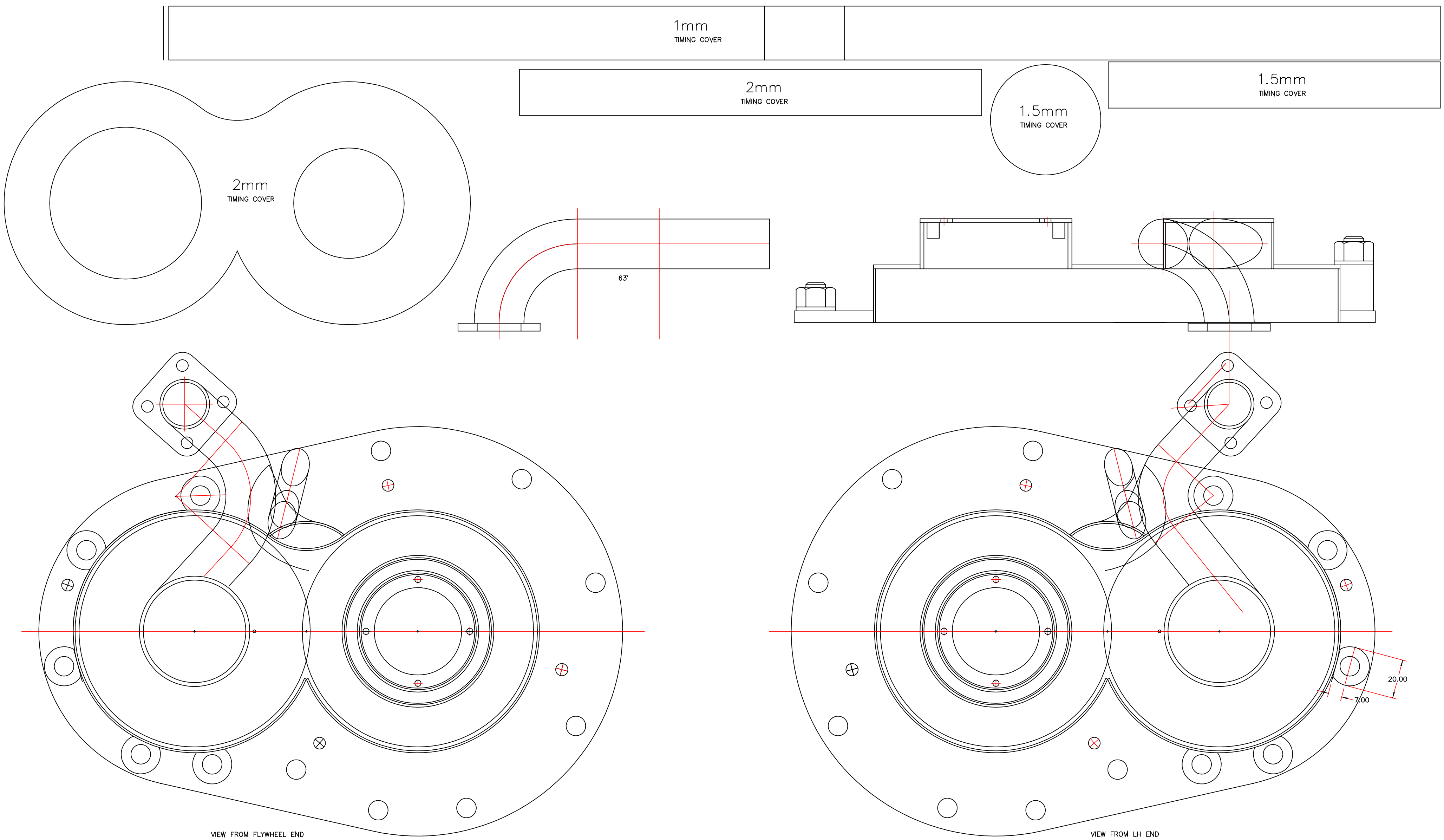
UNSPECIFIED TOLERANCES. 0 ±0.40, 0.0 ±0.15, 0.00 — ±0.07

BHID	FOR	DATE 24 AUG 01	SCALE FULL	PART FEMALE SHAFT
		DRAWN BH.		

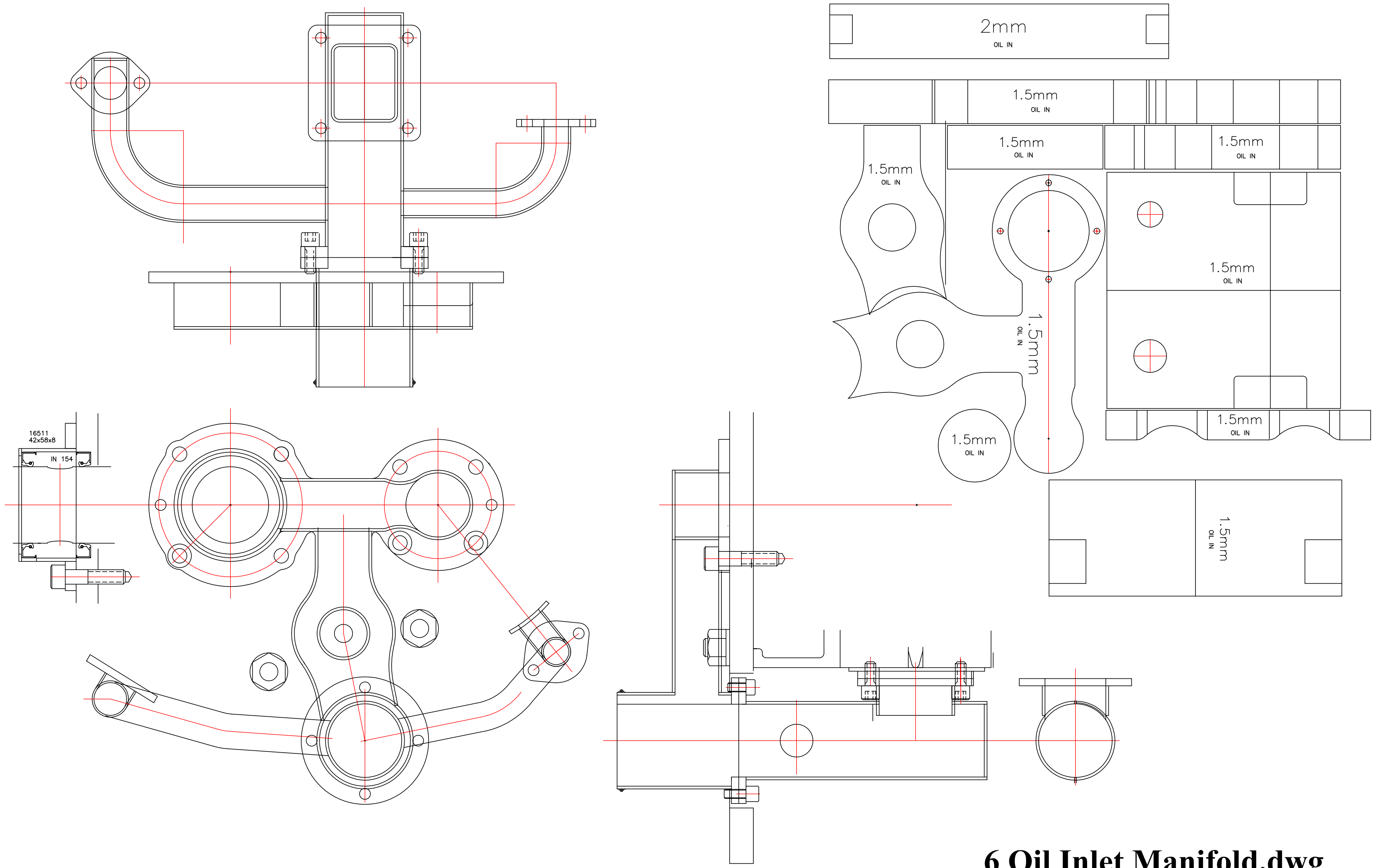
D-27



6 Cover Plates.dwg

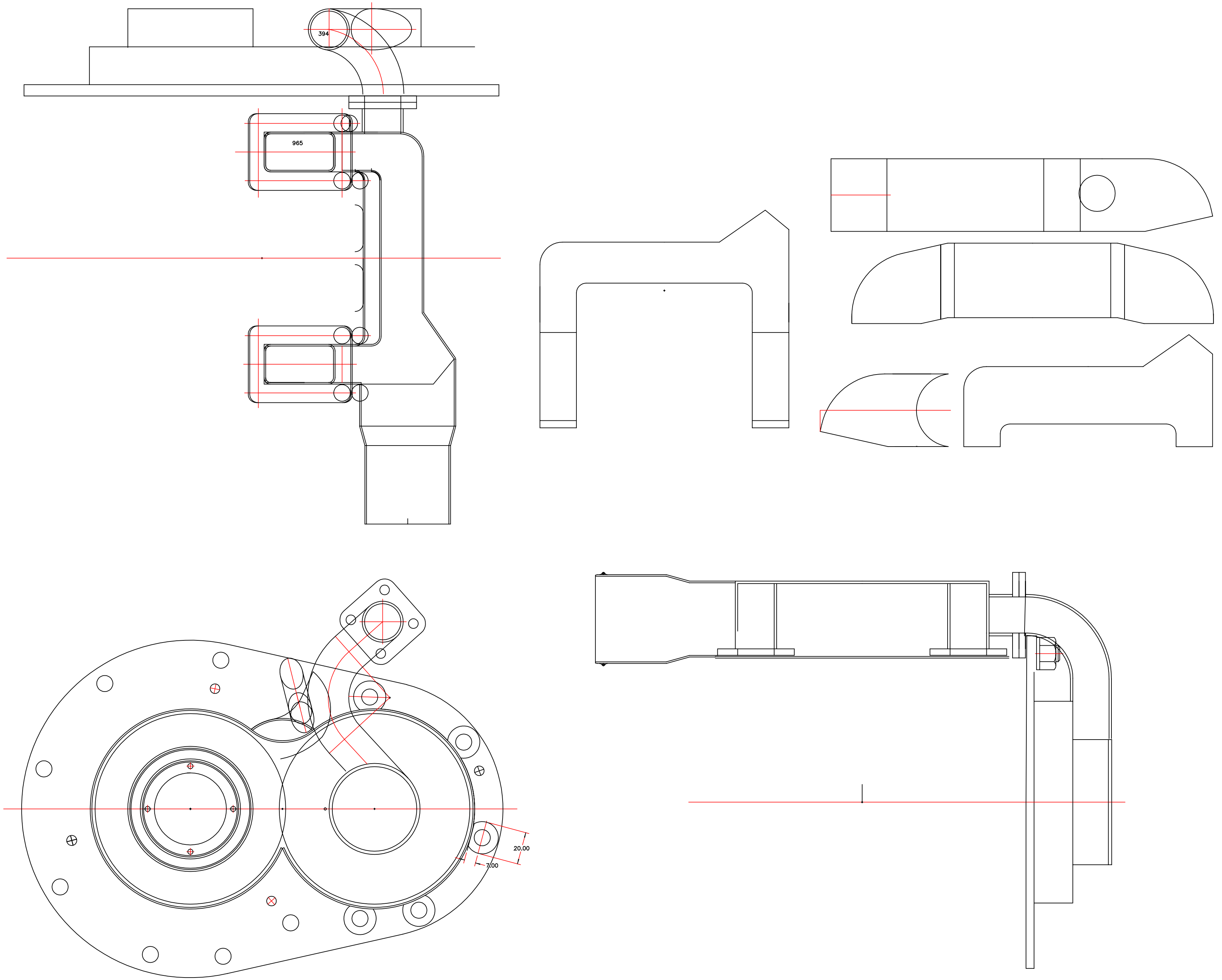


6 Timing Gear Housing.dwg

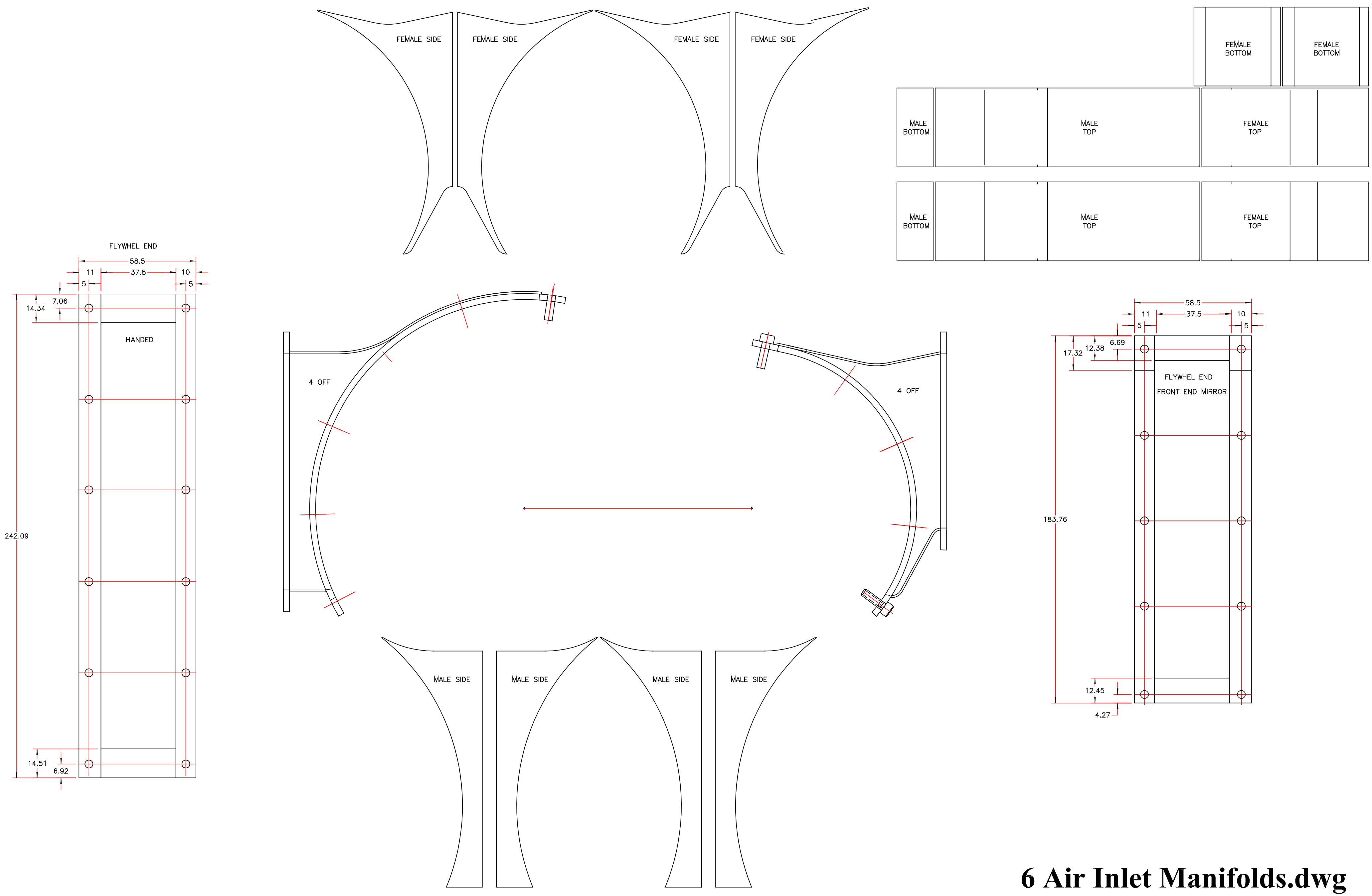


6 Oil Inlet Manifold.dwg

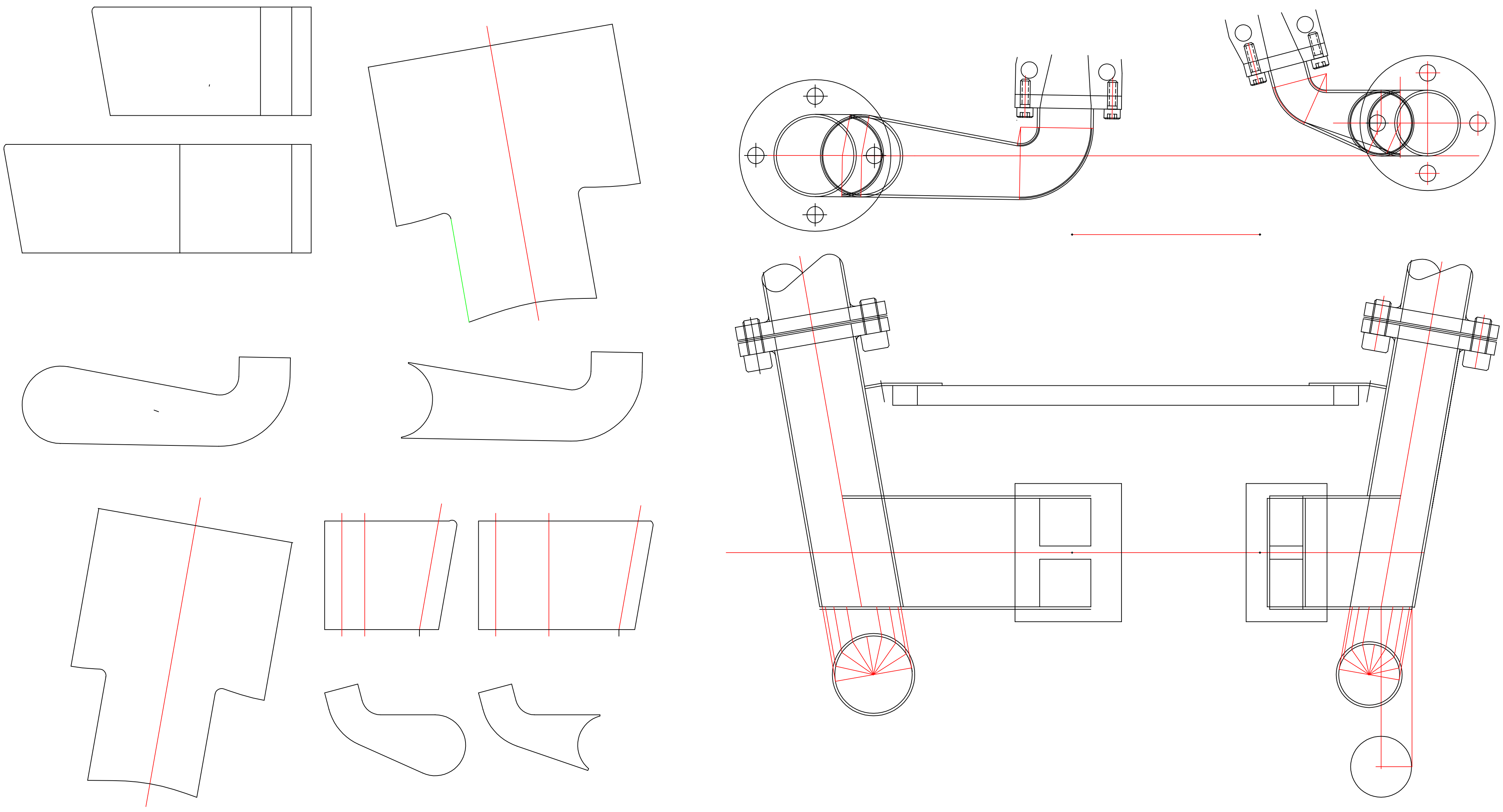
D-30



6 Oil Outlet Manifold.dwg

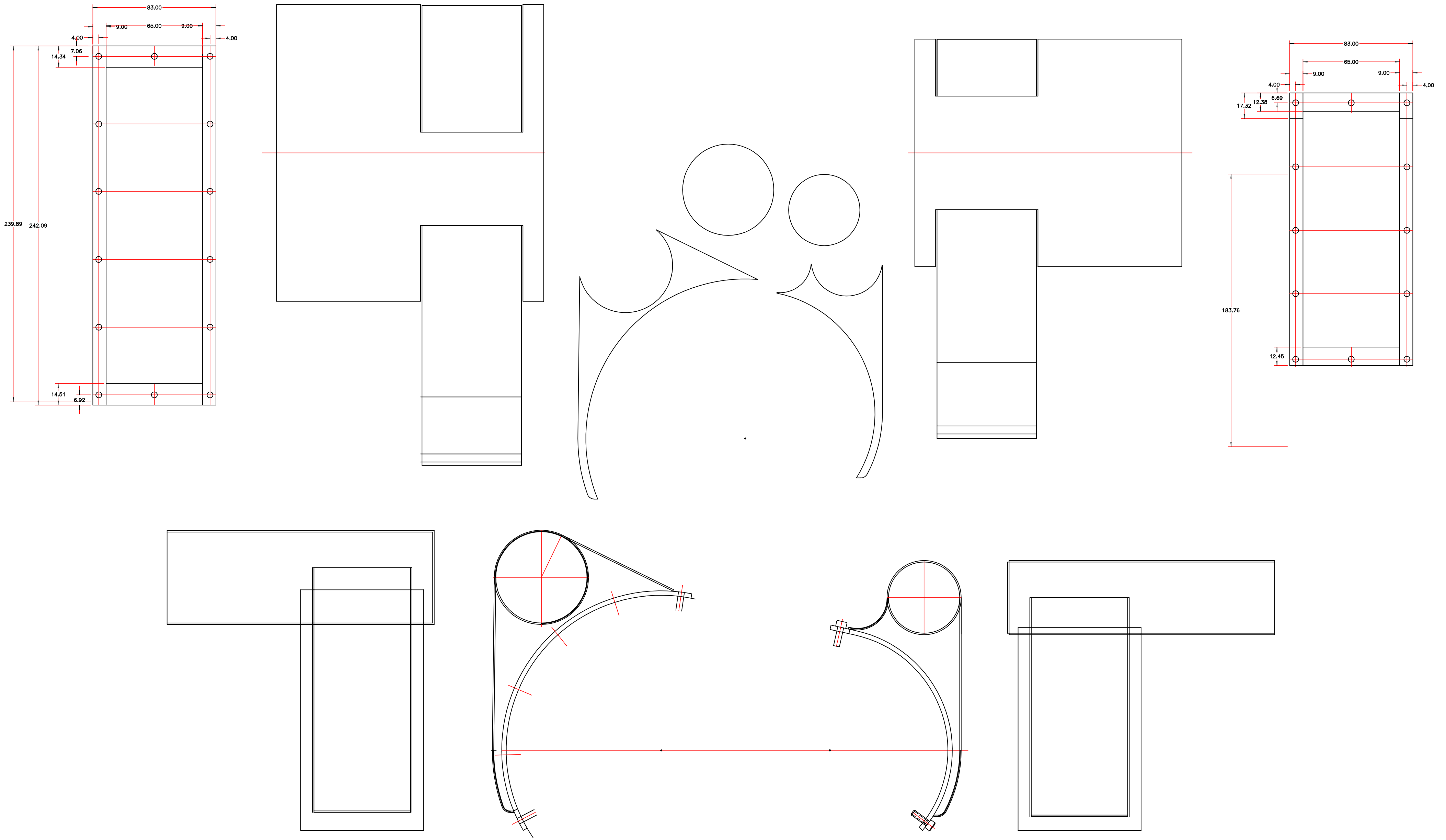


6 Air Inlet Manifolds.dwg



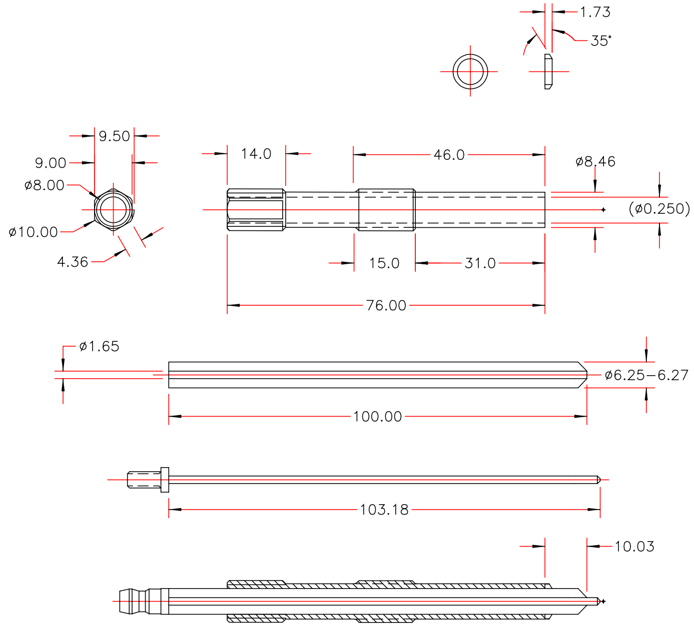
6 Exhaust Manifolds.dwg

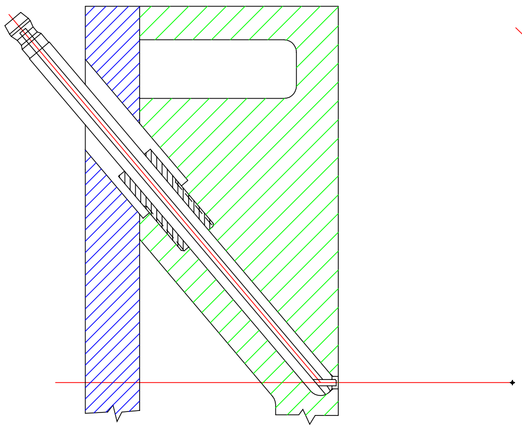
D-33



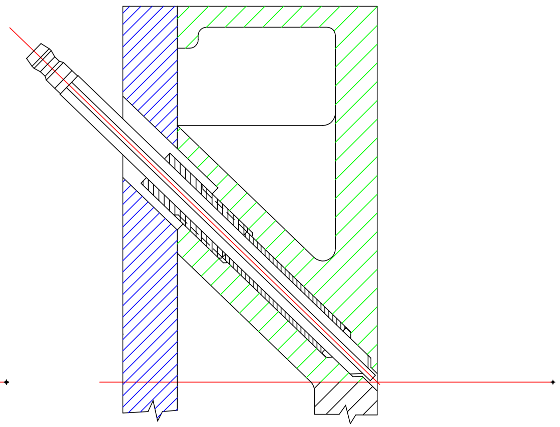
6 Purge Manifolds.dwg

D-34

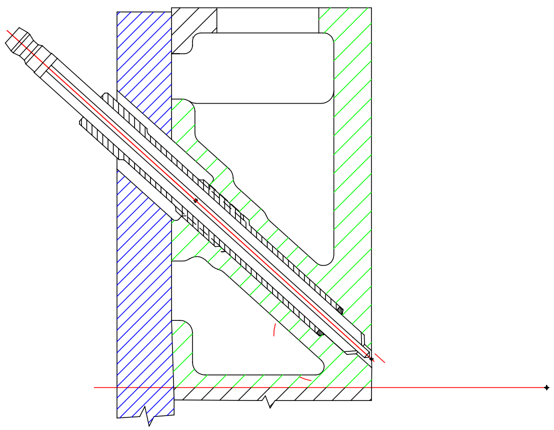




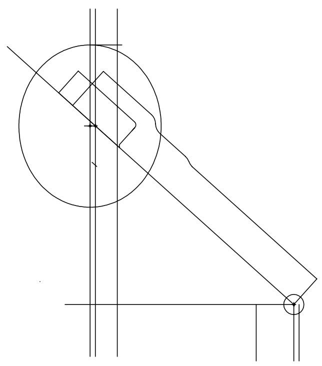
EARLY



LATER

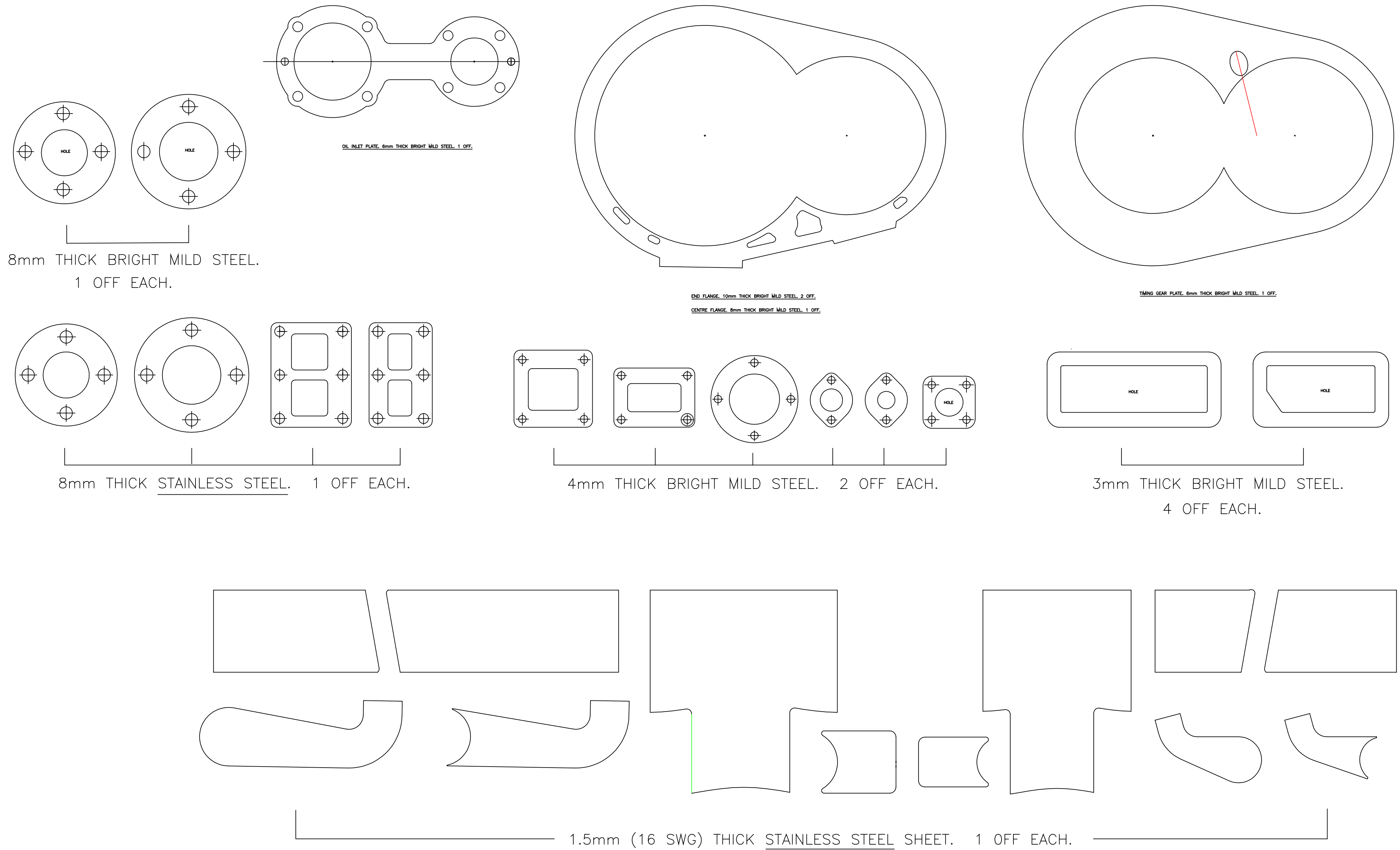


FINAL



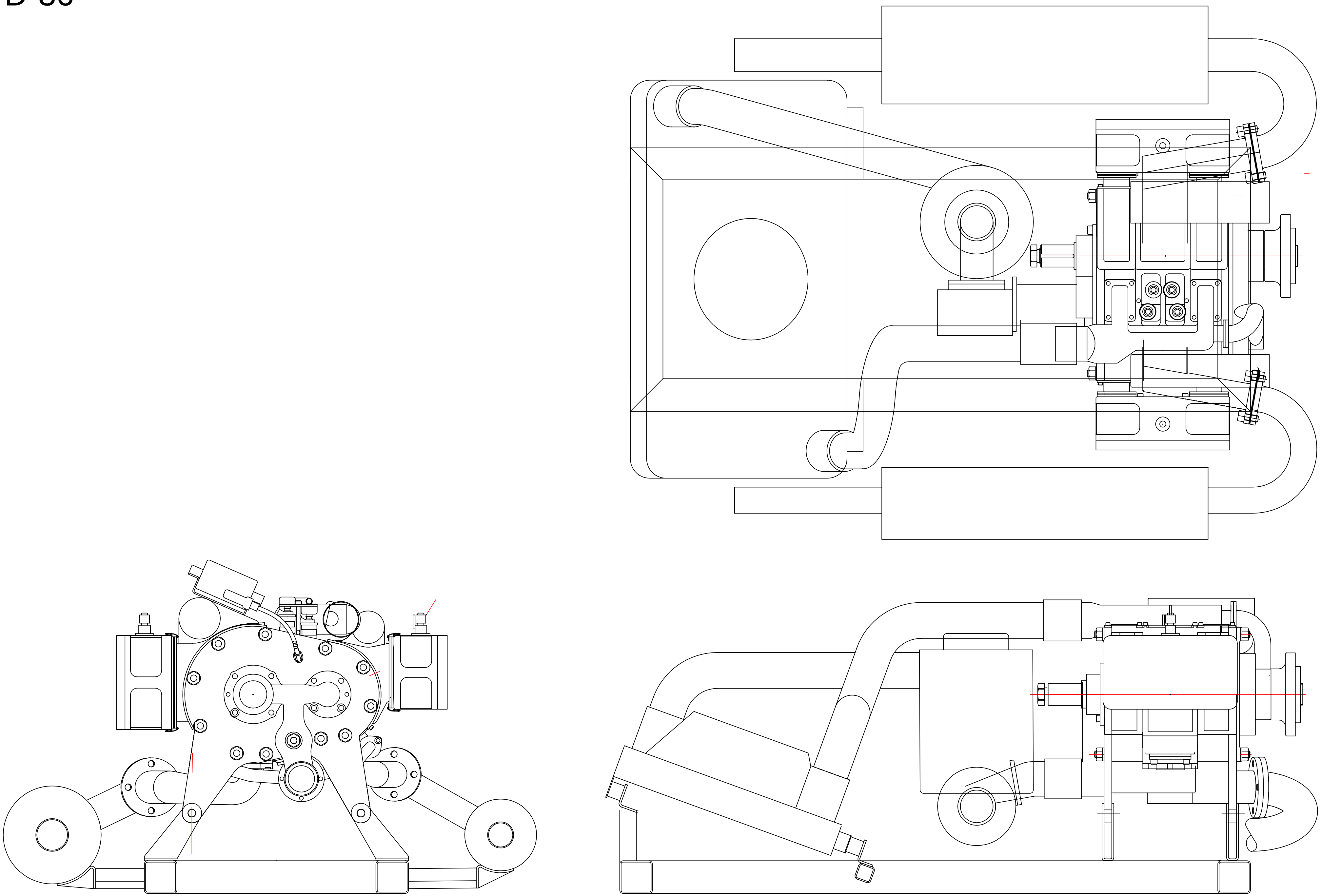
6 Spark Plug.dwg

D-35



6 Laser Cutting Profiles.dwg

D-36



6 Test Bed.dwg